VOLUME 104 PART A NUMBER 15 JUNE 1957

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

SAVOY PLACE · LONDON W.C.2

Price Ten Shillings

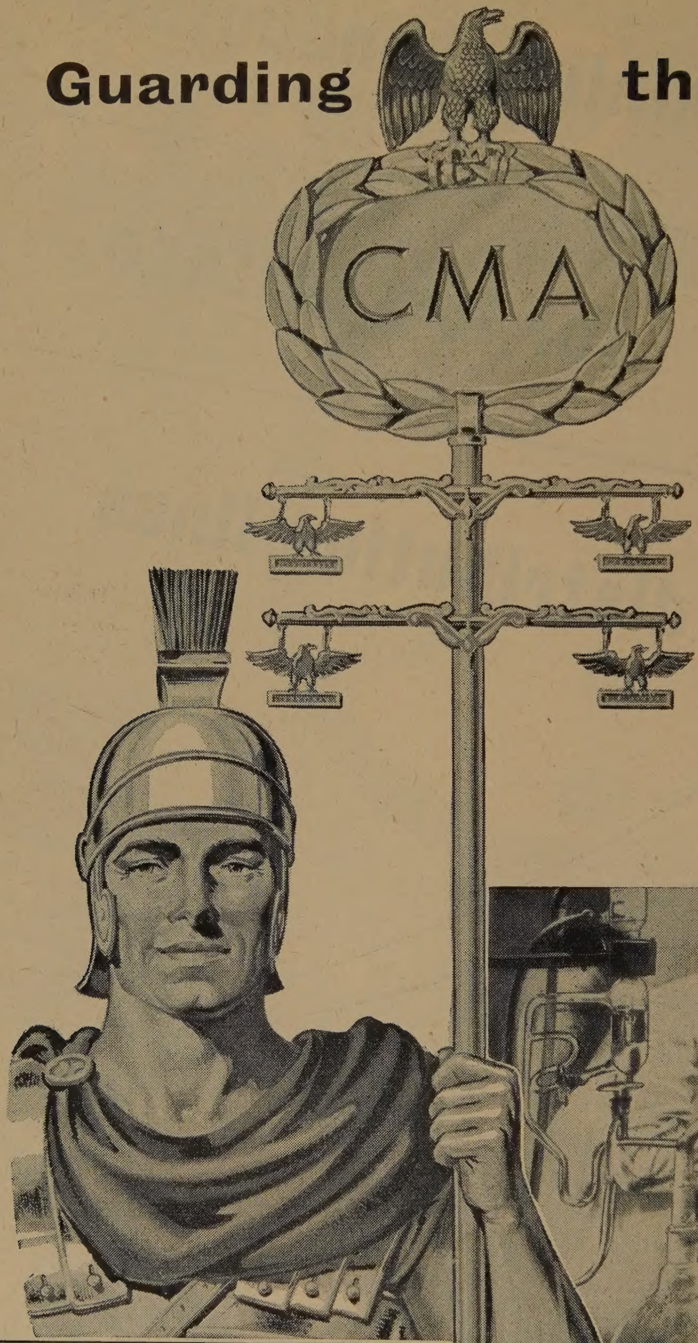
THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871 INCORPORATED BY ROYAL CHARTER 1921

PATRON: HER MAJESTY THE QUEEN

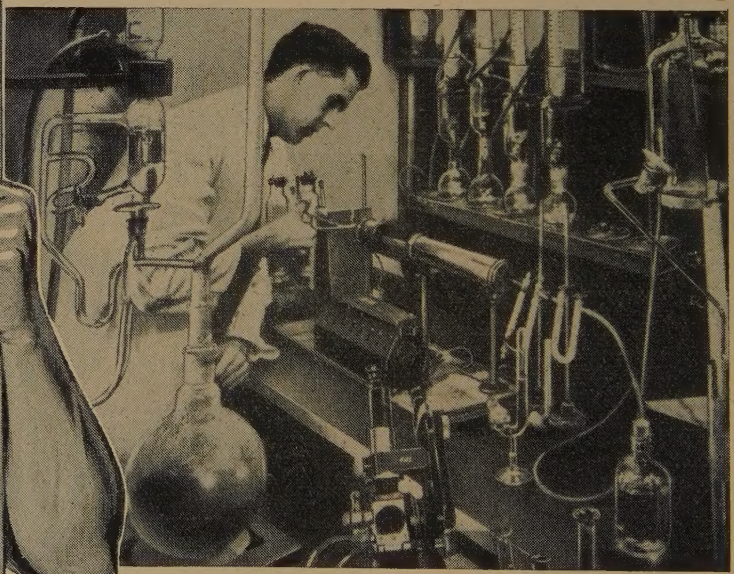
COUNCIL 1956–1957

Guarding the standards . . .



The £1 million allocated to research and development last year by the fifteen members of the Cable Makers Association was money well spent. At every stage from the raw material, shown here being tested in one of the chemical laboratories, to the finished cable, technical knowledge, data and experience is pooled and research co-ordinated to avoid wasted effort. The sole aims are to safeguard the standards and increase the range of C.M.A. products, to meet, and often anticipate, the ever-expanding needs of industry. Such co-ordinated efforts over the past 58 years have played a key role in maintaining Britain as the world's leading exporter of cables. They form an outstanding example of co-operation within an industry for the common good.

The Roman Warrior and the letters 'C.M.A.' are British Registered Certification Trade Marks.



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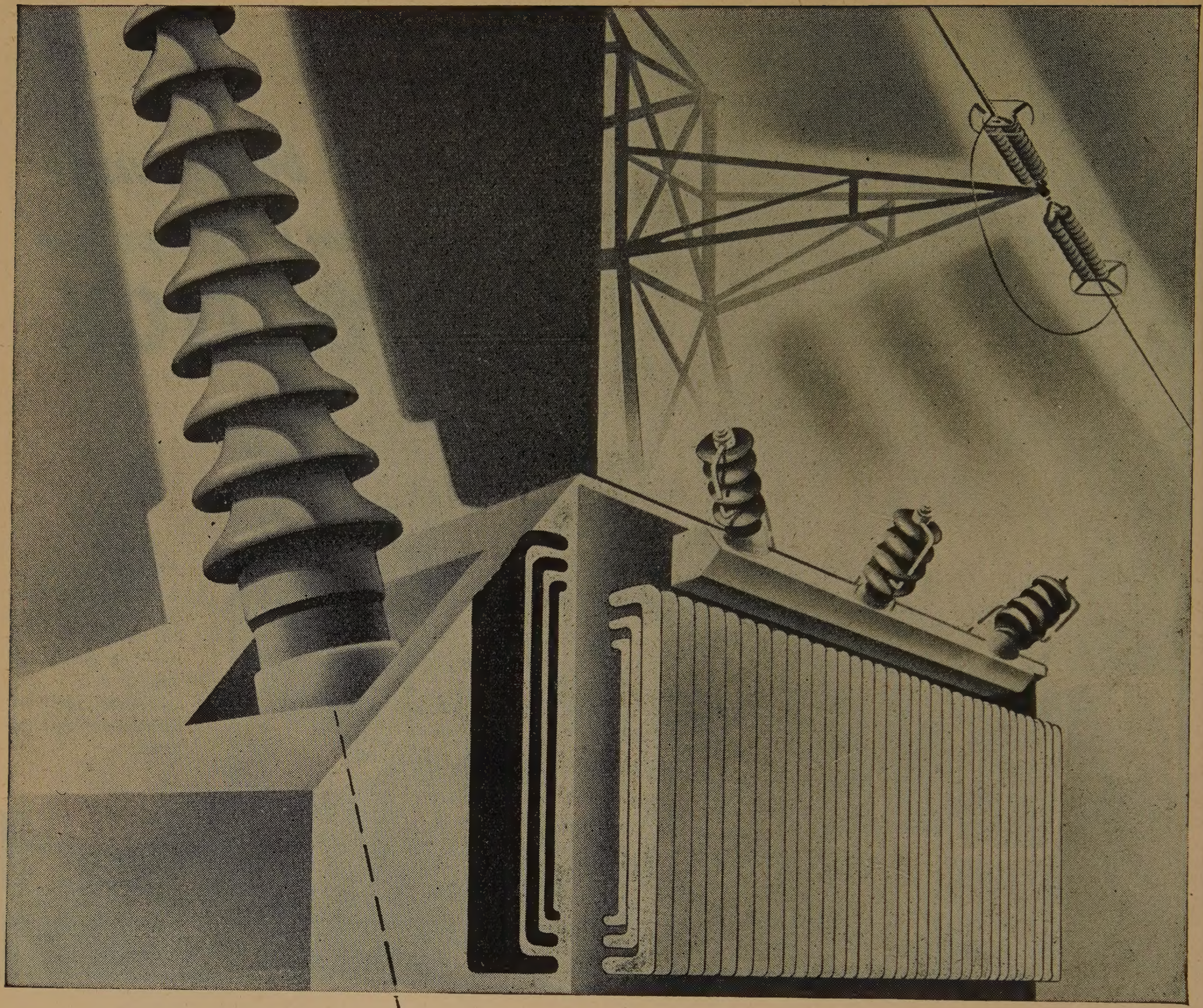

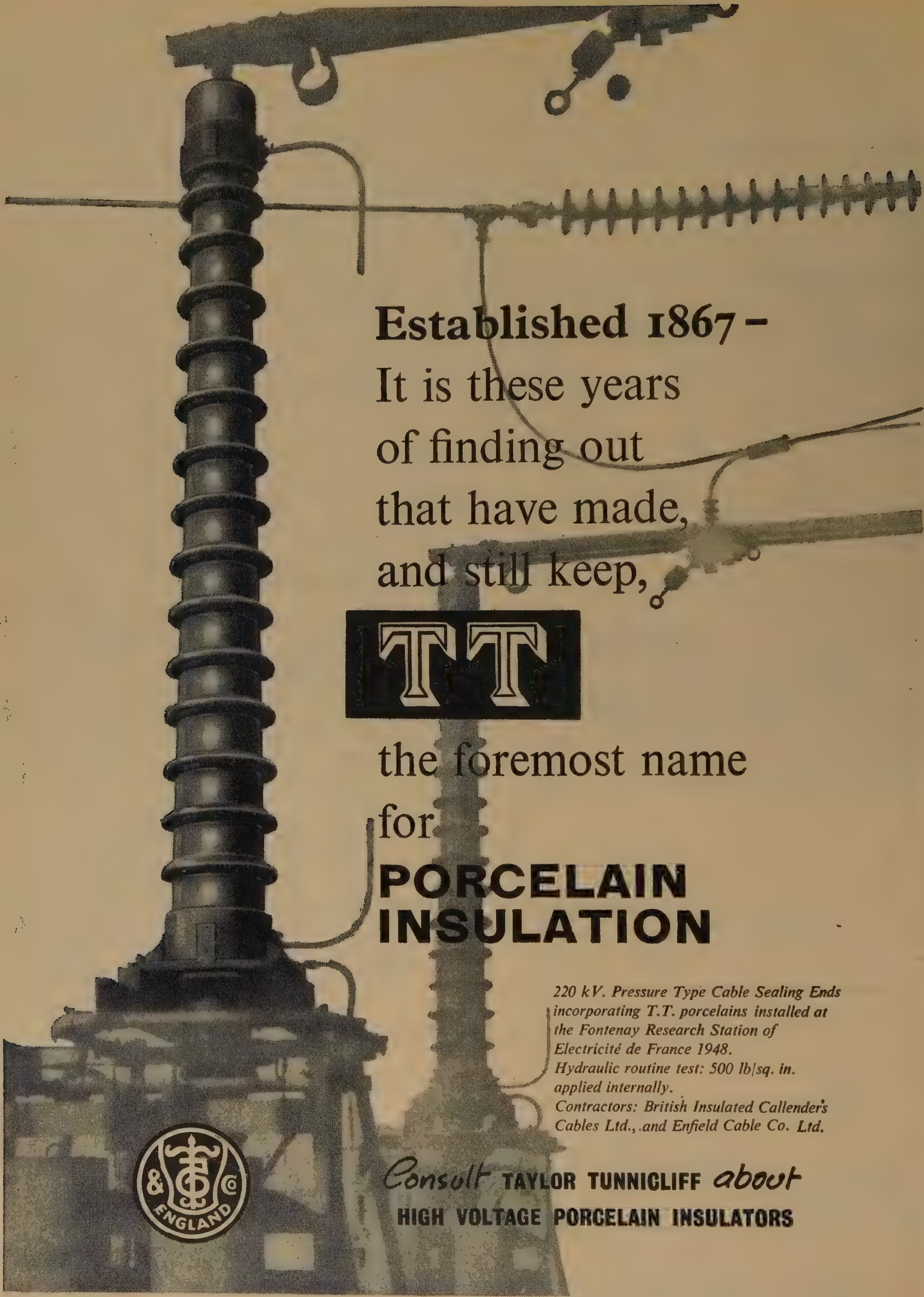
Established 1867 –
It is these years
of finding out
that have made,
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220 kV. Pressure Type Cable Sealing Ends incorporating T.T. porcelains installed at the Fontenay Research Station of Electricité de France 1948.
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Contractors: British Insulated Callender's Cables Ltd., and Enfield Cable Co. Ltd.
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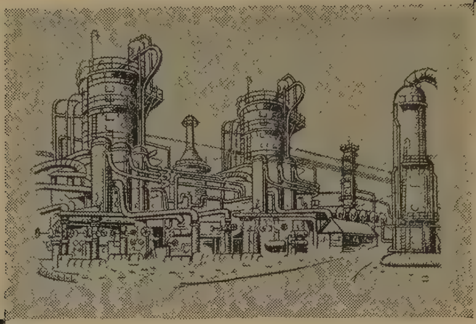
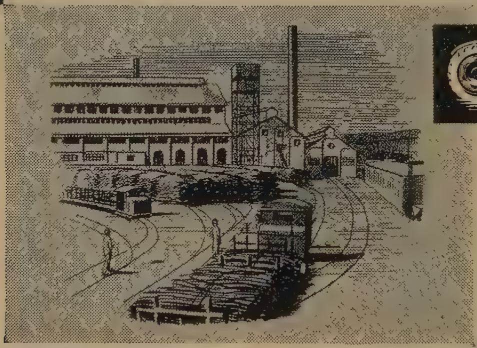
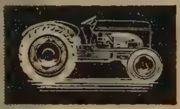


for every



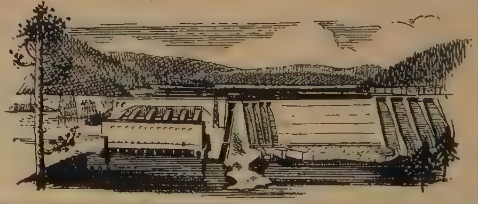


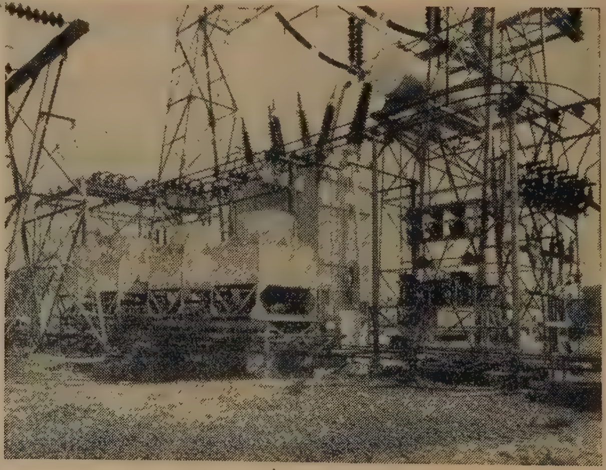
industry

SERCK
MOBILE AIR BLAST TRANSFORMERS
OIL COOLERS

are installed at the SOREL TERMINAL STATION of the Trenche hydro-electric development on the St. Maurice River, Canada.

Photograph by permission of the Shawinigan Engineering Company.





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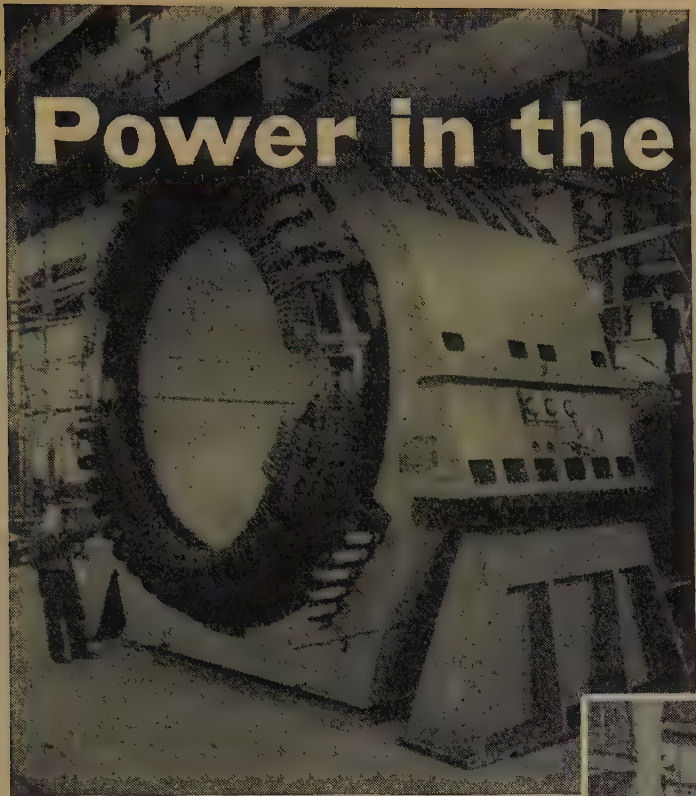
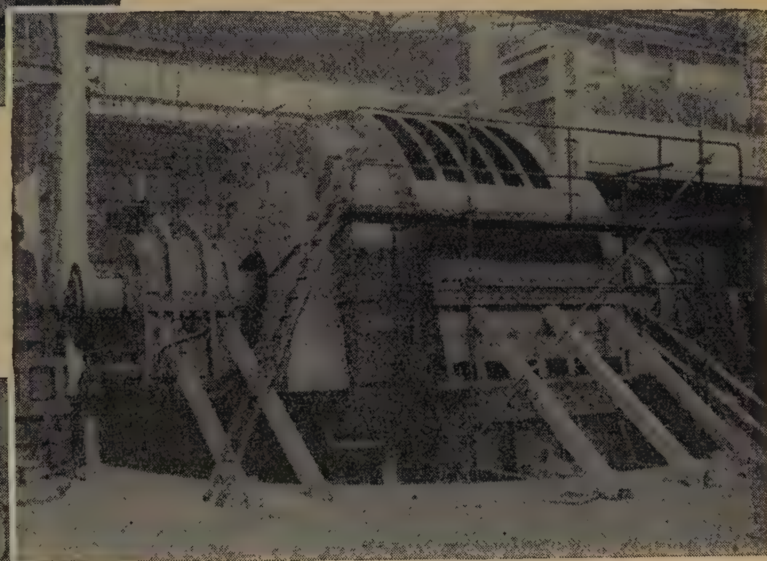
Power in the making...



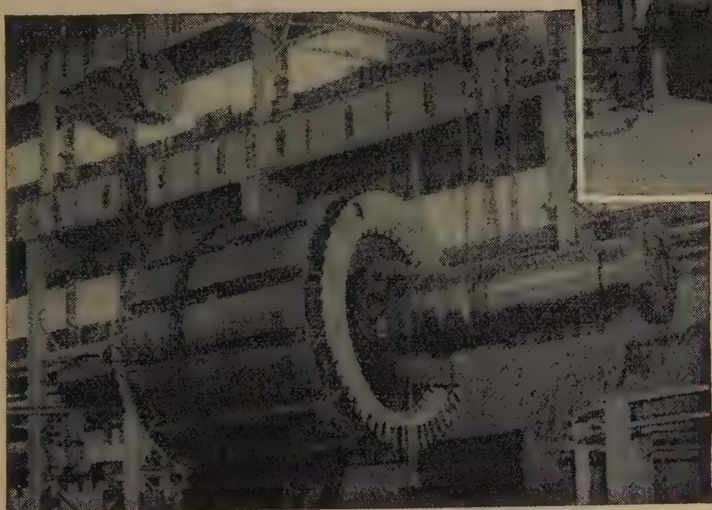
The stator completed

AURA

TWO 62.5 MVA and four 37.5 MVA horizontal water-wheel generators have been manufactured by Metropolitan-Vickers for the Aura hydro-electric station of the Norges Vassdrags-og Elektrisitetsvesen. The photographs illustrate the work in progress on the second 62.5 MVA machine.



The completed set being tested at full load wattless kVA



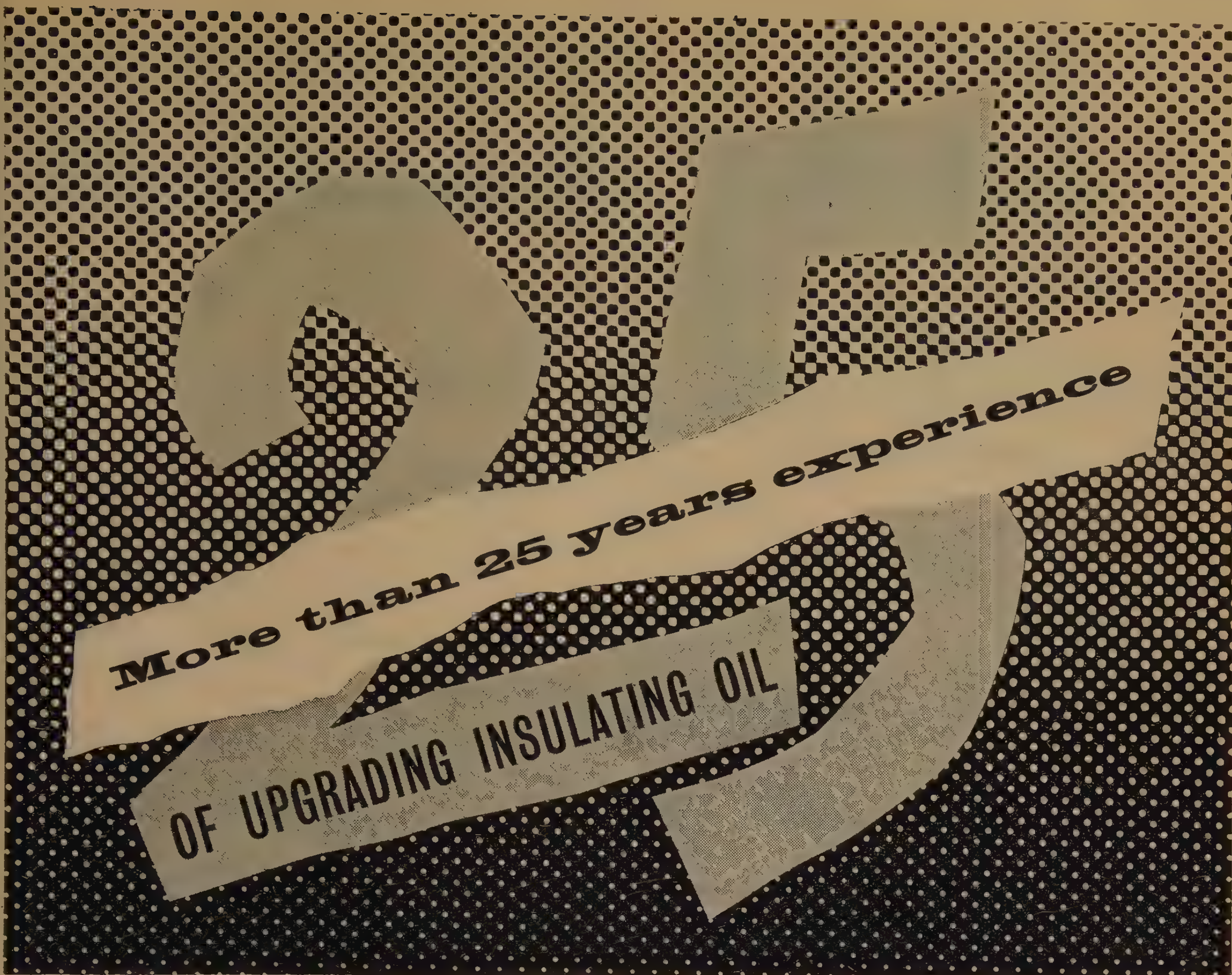
Preparing to thread the rotor into the stator

METROPOLITAN-VICKERS
ELECTRICAL CO LTD TRAFFORD PARK MANCHESTER 17

An A.E.I. Company

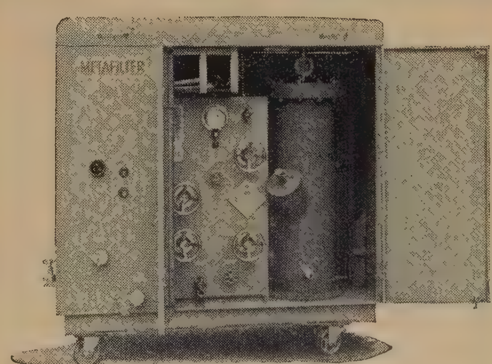
Leading Electrical Progress

C/A 602



For more than a quarter of a century Metafilters have been accepted by electrical engineers for the COLD upgrading of switch and transformer oils. The filtration principle (using Metasil A.W.) is precisely the same as that employed for the removal of bacteria in other applications, thus ensuring absolute removal of solid impurities however finely divided, together with dehydration without recourse to heating and/or vacuum.

Electrical and consulting engineers, well-known oil companies, generating and distributing organisations, manufacturers of transformers and switchgear have chosen the Metafilter because (a) COLD filtration effects removal of impurities otherwise soluble in hot oil, (b) high di-electric strength and (c) no costly expenditure on replacement papers or sheets.



Metafilters for transformer and switch oils are available as static, portable and fully mobile units with capacities from 50 g.p.h. to 1000 g.p.h. Our experience and advice is at your disposal. Please write for Section 7 Catalogue giving details of our latest units.

Metafilter

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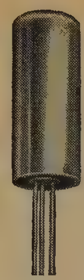
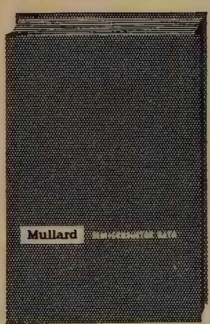
TRANSISTOR NEWS



from Mullard

NEW DATA BOOK LISTS EXTENDED RANGE



A new booklet is available which gives data, curves and application notes on all transistors and diodes in the Mullard extended range. Low power audio types are already in large scale production, while other types have completely passed through development and are on production schedules.

This extended range provides the circuit engineer with a greater choice of types for specific applications. The main trends in the characteristics of the later types have been towards higher frequency performance, greater power handling capacity and towards the improved pulse handling capabilities so necessary for digital computers.

In addition to progress in germanium transistors, research into the large scale production of silicon types actively continues. In this way the Mullard range of semiconductors is rapidly increasing, and already ten types of transistor and eight types of diode are being supplied.

The data booklet is available free of charge from the address below. A request on your Company letterhead will also ensure that you will be mailed further information on Mullard semiconductors as it is issued.

MULLARD LIMITED, COMMUNICATIONS AND INDUSTRIAL VALVE DEPARTMENT

Mullard

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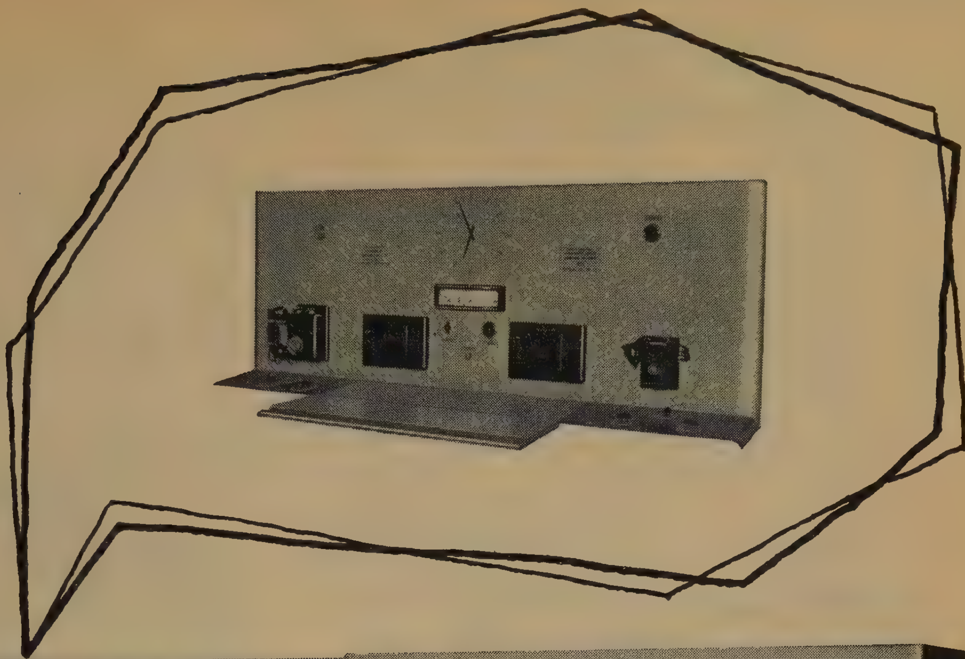
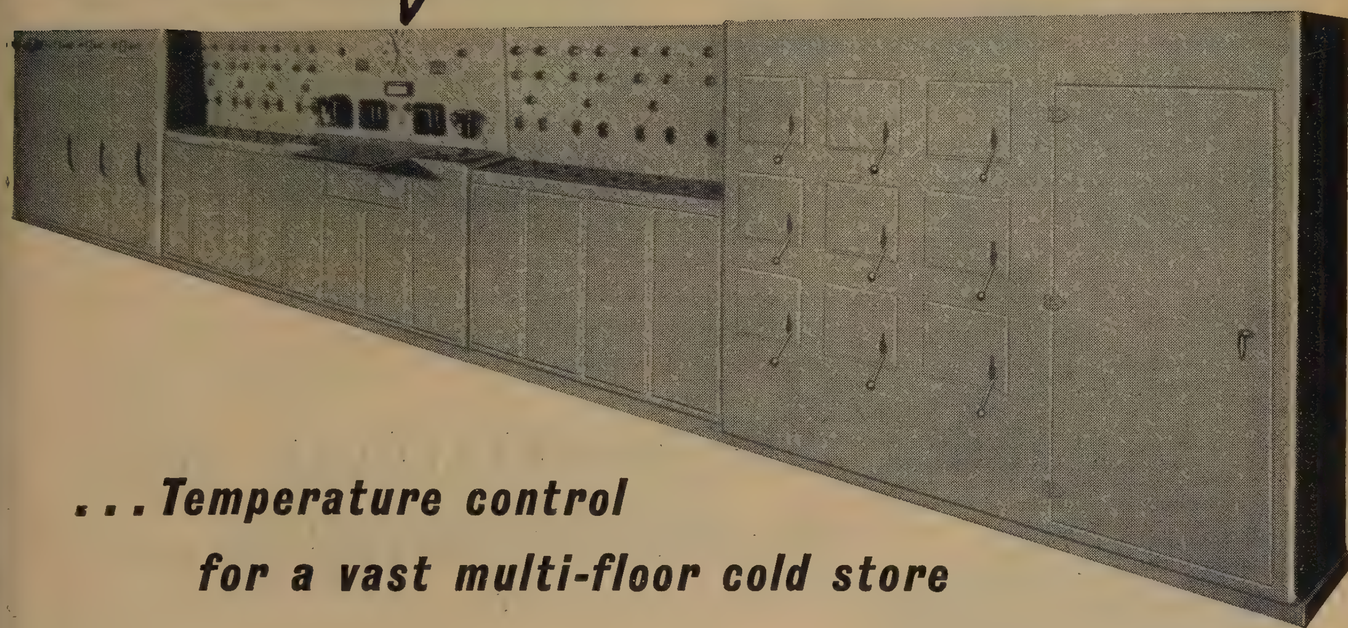
MVT. 309





Space-saving...

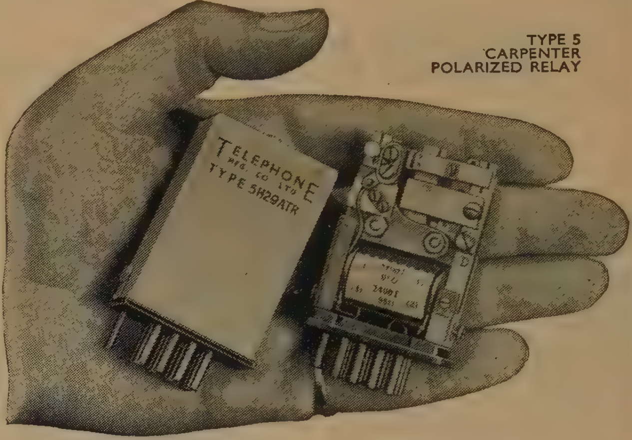
and the **Carpenter Polarized Relay**

The urgent need for space-saving in modern equipment design is well met by Carpenter Relays, for the smaller types are no larger than an ordinary match-box . . . yet they are highly sensitive, very fast in operation with minimum contact bounce, and maintain accurate adjustment in arduous conditions of wide variations of temperature, acceleration and vibration.

Because of their small size and reliably excellent performance they are used in a wide variety of aircraft equipment—and, because they are also economical in cost, are incorporated in many Industrial recording, Temperature Control and Servo-Mechanisms.

Therefore, if you are interested in circuits involving *Control, Amplification, Impulse repetition* and *High-speed Switching*, where limited space is a ruling factor, ask us to send you details of the Types 5, 6 and 51 Carpenter Polarized Relays.

TYPE 5
CARPENTER
POLARIZED RELAY



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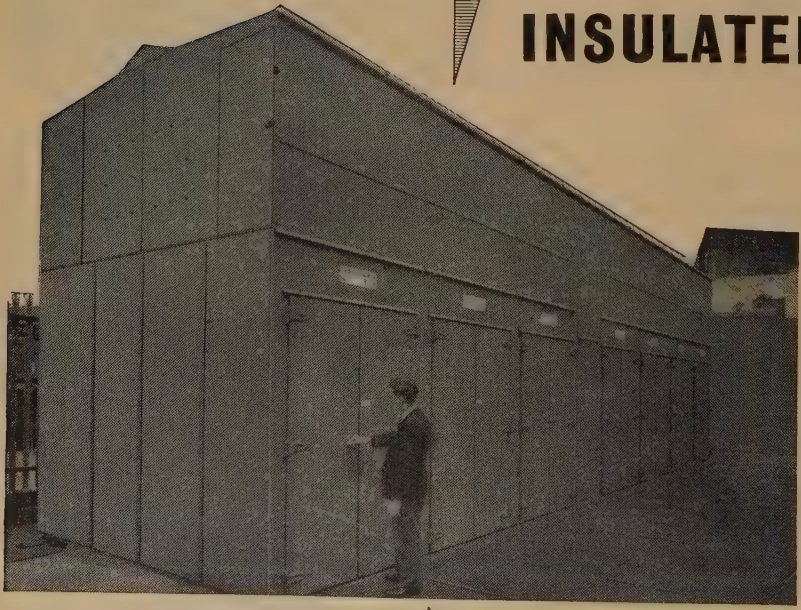
SWS 33-kV METALCLAD AIR INSULATED SWITCHGEAR



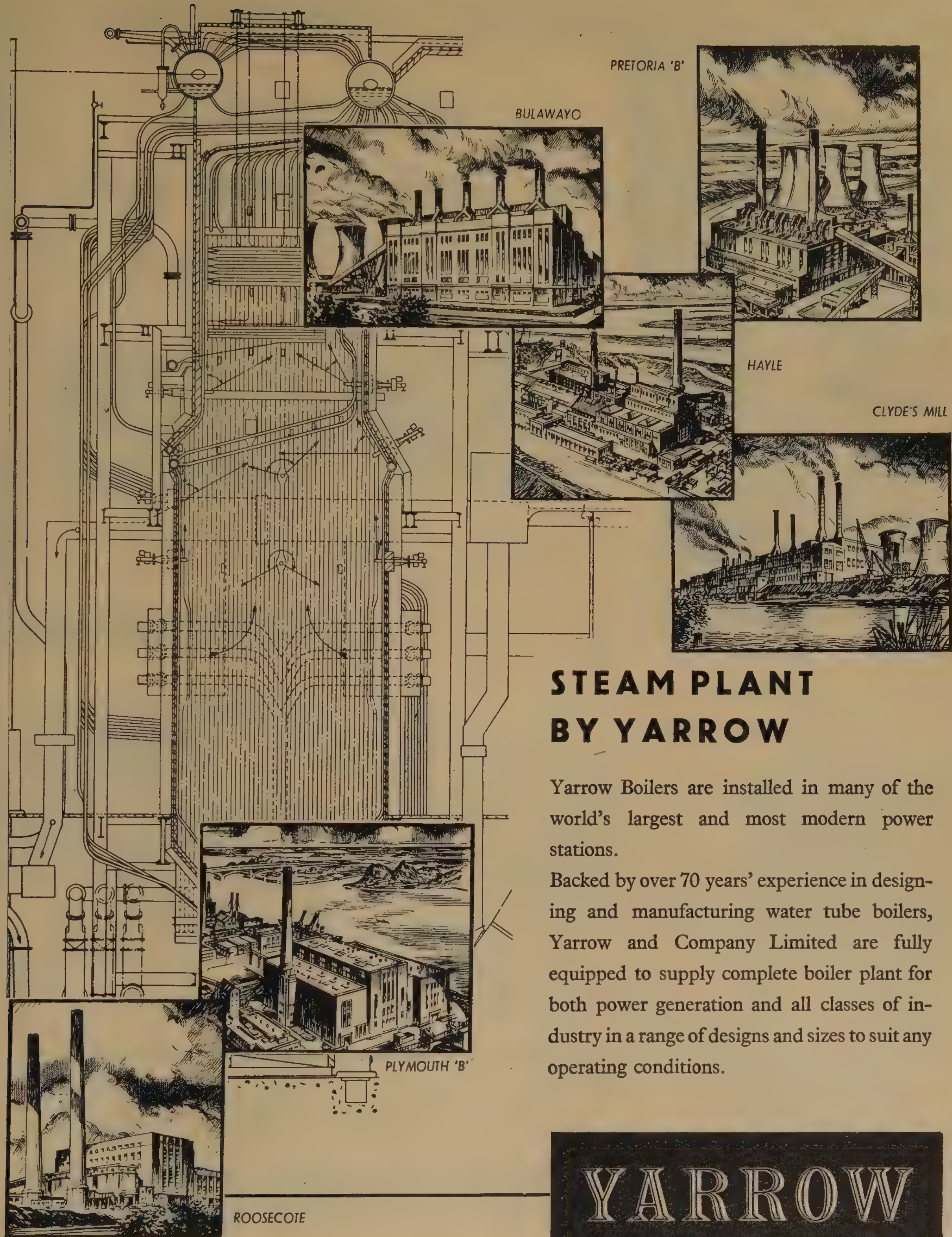
This unit, the first of its type produced in Britain, is designed to provide economic switchgear for 33-kV networks.

- Economy in Space—Seven-unit substation of UE1 equipments, occupies only 1/10 the space of a conventional outdoor station.
- Economy in Construction—A seven unit switchboard was installed in three weeks from the laying of the foundation frames.
- Economy in Siting—As the unit requires only a fraction of the space of an open type layout there is greater flexibility in the choice of site.
- Ease of Maintenance—Motor operated mechanism raises or lowers the oil circuit breaker to permit inspection and maintenance in all weather conditions.

For further details please write for publication No. 542

SOUTH WALES SWITCHGEAR LIMITED
BLACKWOOD · MONMOUTHSHIRE Works at Treforest and Blackwood.
SWITCHGEAR · SWITCHFUSEGEAR · TRANSFORMERS · CONTROL BOARDS

TGAG23



STEAM PLANT BY YARROW

Yarrow Boilers are installed in many of the world's largest and most modern power stations.

Backed by over 70 years' experience in designing and manufacturing water tube boilers, Yarrow and Company Limited are fully equipped to supply complete boiler plant for both power generation and all classes of industry in a range of designs and sizes to suit any operating conditions.

YARROW & CO LTD SCOTSTOUN GLASGOW
Tel: Scotstoun 2228

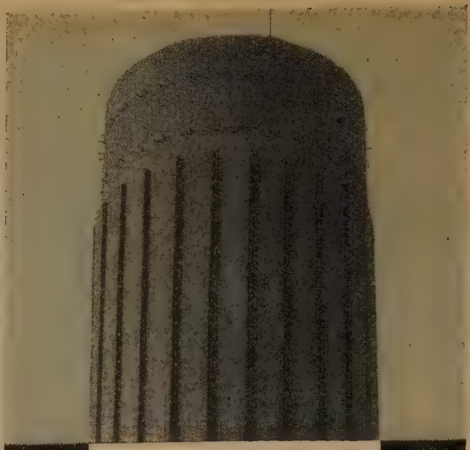
YARROW
BOILERS

Right—from the start

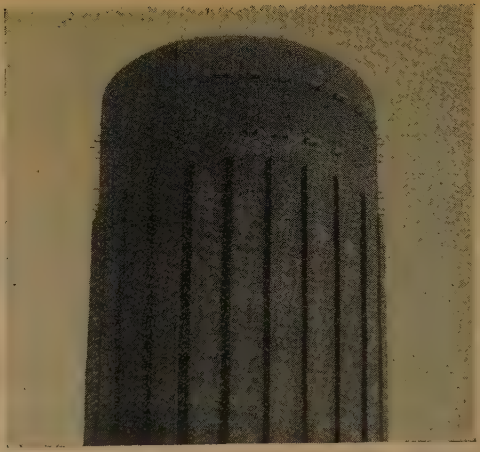
At the Fleetwood power station of the Central Electricity Authority, where the first boiler was commissioned in May 1955, the first two boilers have each steamed for some ten thousand hours. During this time there has been no sign of any dust build-up on the chimney cap—shown here in unretouched photographs. The total number of hours during which any part of the electro-precipitator has been out on fault is less than 24 and at no time has the complete precipitator been out on fault.

This is a striking testimony that the Simon-Carves electro-precipitators, which extract the flue dust produced by the three boilers at the station, have worked effectively from the time they were first brought into operation.

Because their design is based on long experience of electro-precipitation techniques coupled with up-to-date knowledge of the latest developments, Simon-Carves electro-precipitators are right—from the start.



99·36% EFFICIENCY In the acceptance test of steam generating plant and electro-precipitators for Boiler No. 2 at the Fleetwood power station of the North West, Merseyside and North Wales division of the Central Electricity Authority the efficiency achieved by the electro-precipitators was 99·36% at maximum continuous rating.



Unretouched telephoto views of the chimney cap at Fleetwood power station, from (left) the north and (above) the south.

***High efficiency electro-precipitation by* Simon-Carves Ltd**
STOCKPORT, ENGLAND

SIMON ENGINEERING GROUP

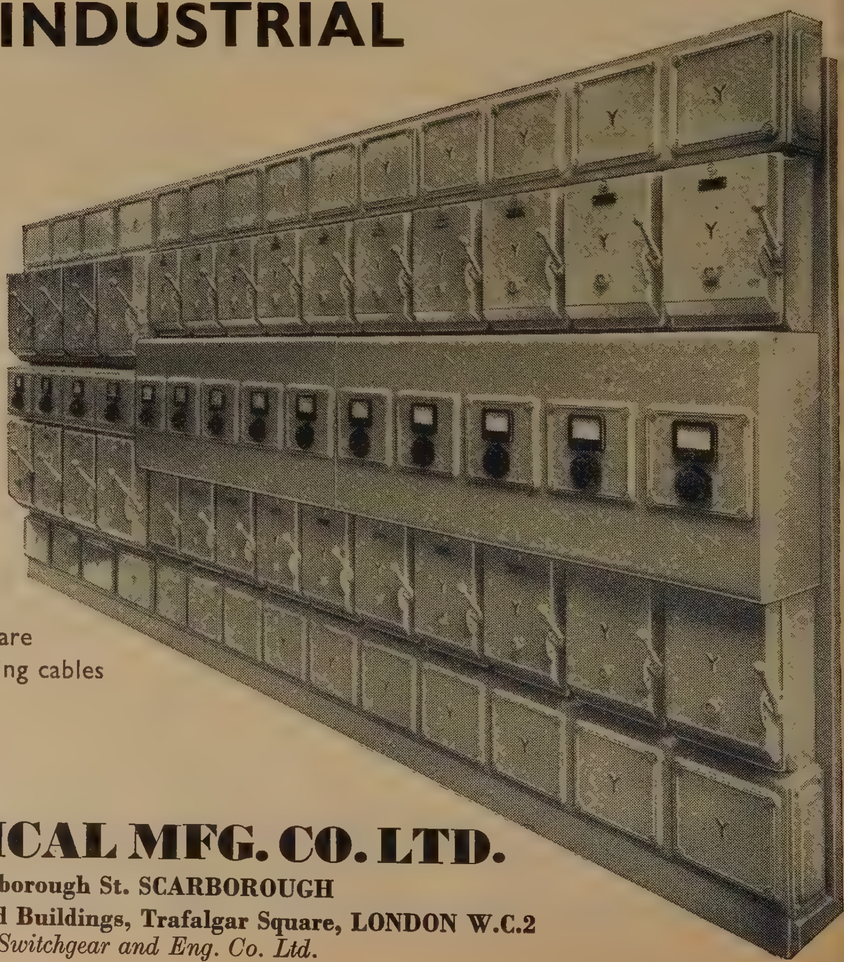
OVERSEAS COMPANIES | *Simon-Carves (Africa) (Pty) Ltd: Johannesburg Simon-Carves (Australia) Pty Ltd: Botany, N.S.W.*

SC 175

UNIT TYPE "Y" INDUSTRIAL SWITCHGEAR

(METALCLAD)

FOR INDOOR OR OUTDOOR SERVICE ANYWHERE



Indoor totally enclosed unit construction type "Y" switchboard with incoming duplicate busbars feeding common outgoing circuits by means of interlocked fused switches of both 300 amp and 500 amp capacity. Duplicate busbars are directly connected at the rear to the incoming supply. Current Transformers are mounted in each outgoing chamber, and outgoing cables are from the back.

Supplied to Courtaulds Ltd.

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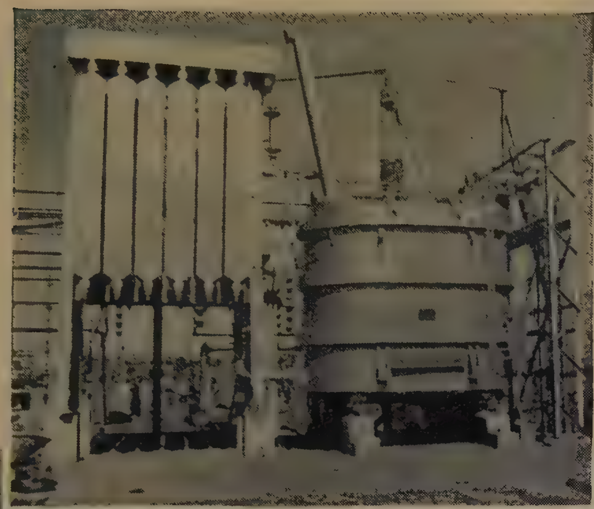
Associated with Yorkshire Switchgear and Eng. Co. Ltd.

More Power for Australia...

B T-H

220 kV TRANSFORMERS



Industrial expansion in Australia has, inevitably, increased the demand for electric power. As part of their development programme, the State Electricity Commission of Victoria are installing a total of seventeen BTH 220 kV, 15 MVA, single-phase transformers at substations in the Melbourne area.

The illustration shows part of the installation at Brunswick substation with, inset, one of the BTH units.

BTH manufacture all types of transformers—also cast-in-concrete and oil-immersed reactors, step-voltage regulators, arc-suppression coils, oil-testing sets, oil filter presses.

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THE BRITISH THOMSON-HOUSTON COMPANY LIMITED · RUGBY · ENGLAND

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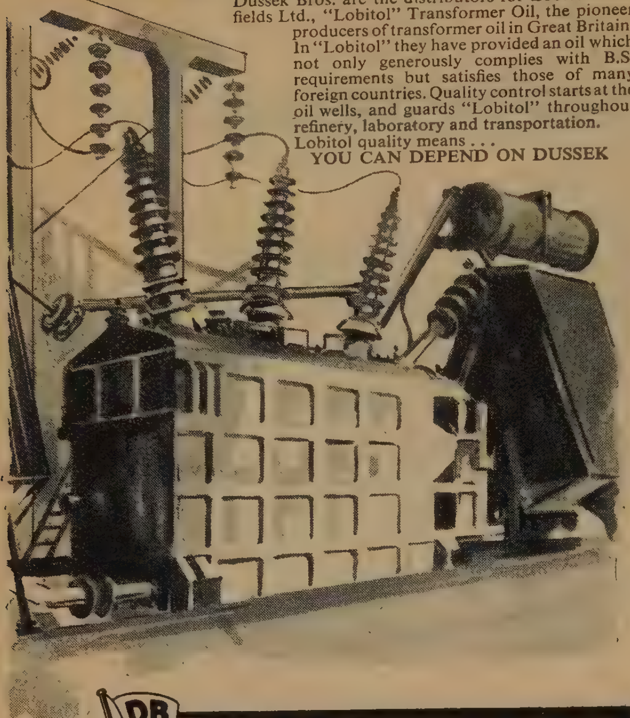
THE DEPENDABLE TRANSFORMER OIL

Dussek Bros. are the distributors for Lobitols Oilfields Ltd., "Lobitol" Transformer Oil, the pioneer producers of transformer oil in Great Britain. In "Lobitol" they have provided an oil which not only generously complies with B.S. requirements but satisfies those of many foreign countries. Quality control starts at the oil wells, and guards "Lobitol" throughout refinery, laboratory and transportation. Lobitol quality means . . .

YOU CAN DEPEND ON DUSSEK



DB ESTD. 1850

DUSSEK BROTHERS & CO., LTD.

THAMES ROAD, CRAYFORD, KENT.

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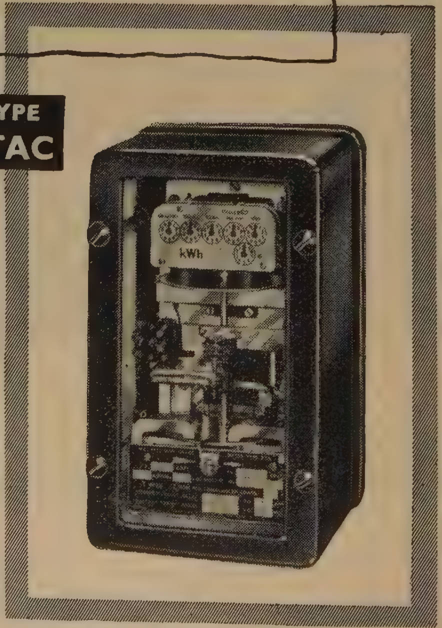
One of the C & H "K" Series of Meters

TYPE KTAC

**3 PHASE
3 WIRE
PRECISION
PATTERN
with "FLICK"
CONTACTOR**



Please apply to us for appropriate Catalogue Sections covering the "K" series of meters.

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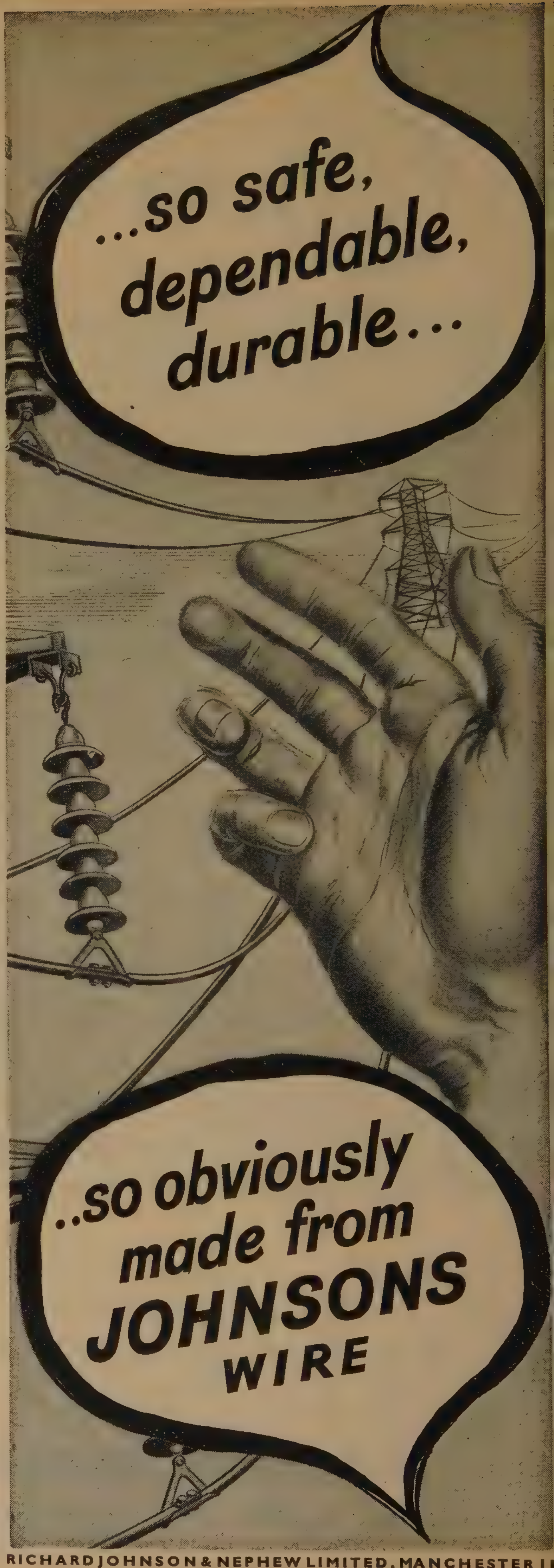
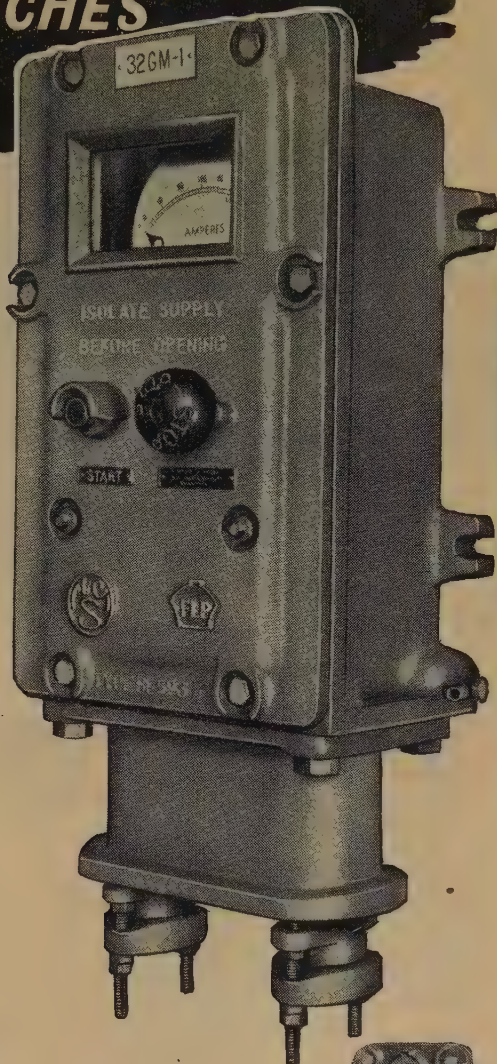
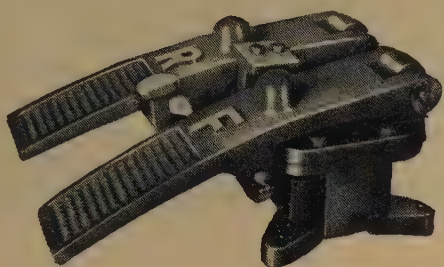


RICHARD JOHNSON & NEPHEW LIMITED, MANCHESTER 11

PUSHBUTTON SWITCHES



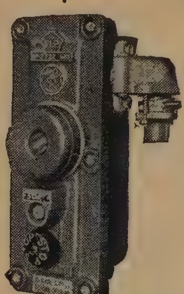
Flameproof 2-point start/stop switch with ammeter. Tropicalised ammeter can be provided.



Hoseproof Twin Pedal Control Switch for use in conjunction with a contactor starter. Arranged for forward and reverse operations.

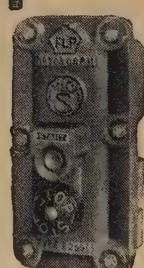
2-point start/stop switch with ammeter.

Flameproof 2-point start/stop switch with indicating lamp.



2-Point start/stop switch.

Flameproof 2-Point start/stop switch.



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M. & C. SWITCHGEAR, LTD.

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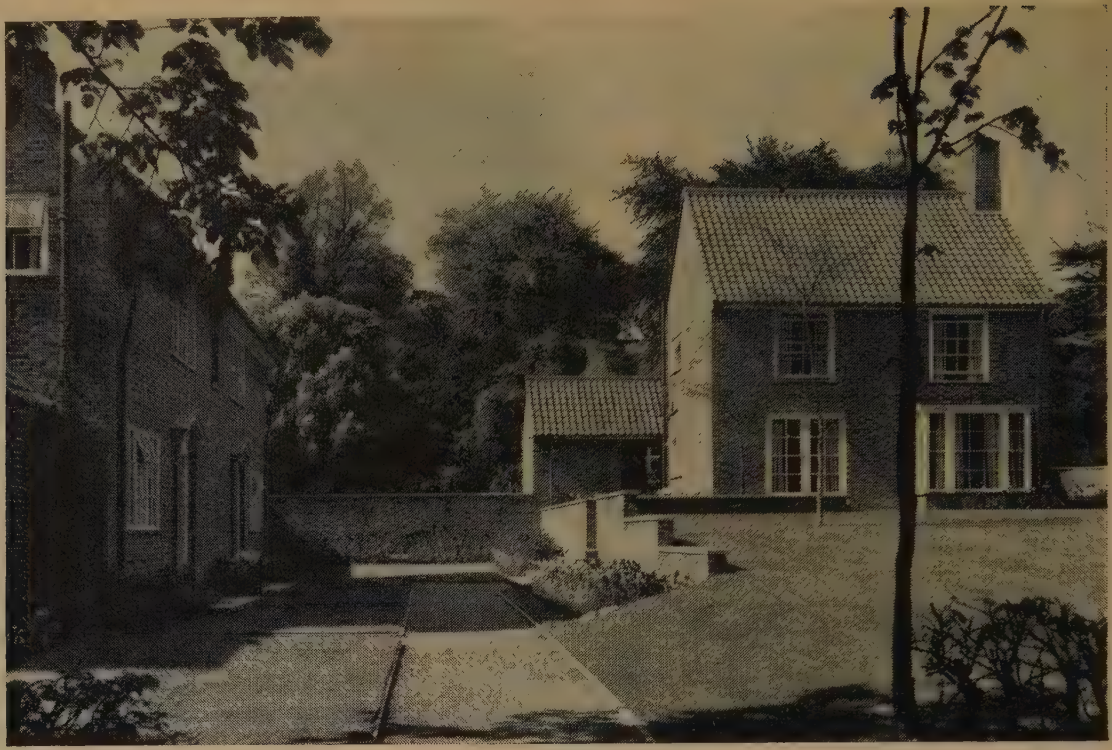
LONDON OFFICE, 36 VICTORIA ST., S.W.1. SHEFFIELD OFFICE, OLIVE GROVE RD.



the homes fund

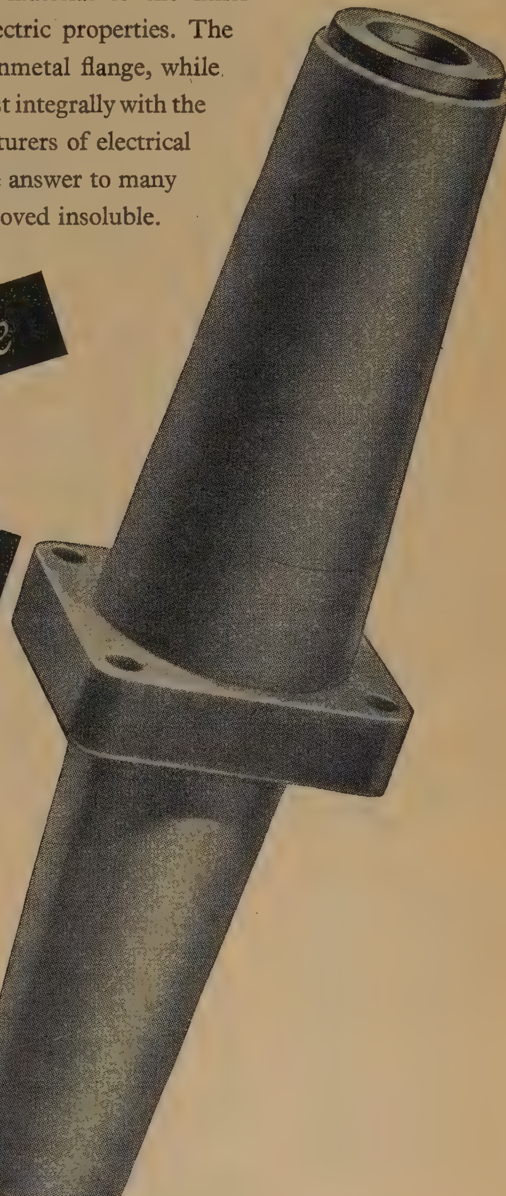
"The Chesters," at New Malden, Surrey,
is a residential estate for members of The Institution or their dependants whose needs have come to the notice of the Court of Governors of the Benevolent Fund.
Funds are still needed to complete the original scheme of 26 *residences.*

★ CONTRIBUTIONS HOWEVER SMALL ARE WELCOMED AND MAY BE SENT TO THE HON. SECRETARY OF THE INCORPORATED BENEVOLENT FUND, THE INSTITUTION OF ELECTRICAL ENGINEERS, SAVOY PLACE, LONDON, W.C.2, OR HANDED TO ONE OF THE LOCAL HON. TREASURERS OF THE FUND.

In addition to its remarkable adhesion to metals and ceramics, 'Araldite' has excellent electrical characteristics, high resistance to moisture and great stability.

The illustrations show two types of bushing developed by Crompton Parkinson Limited to take advantage of the valuable properties of 'Araldite' for electrical applications. In each example the insulation is formed of solid gravity cast 'Araldite', utilizing the excellent void-free adhesion of this material to the inner brass tube and its outstanding dielectric properties. The 11kV bushing on the left has a gunmetal flange, while the other bushing has the flange cast integrally with the insulation in 'Araldite'. Manufacturers of electrical equipment find in 'Araldite' the answer to many problems that have hitherto proved insoluble.

Stable companions



'Araldite' epoxy resins have a remarkable range of characteristics and uses:

They are used
- ★ for bonding metals, porcelain, glass, etc.
- ★ for casting high grade solid insulation
- ★ for impregnating, potting or sealing electrical windings and components
- ★ for producing glass fibre laminates
- ★ for producing patterns, models, jigs and tools
- ★ as fillers for sheet metal work
- ★ as protective coatings for metal, wood and ceramic surfaces

'Araldite' *epoxy resins*

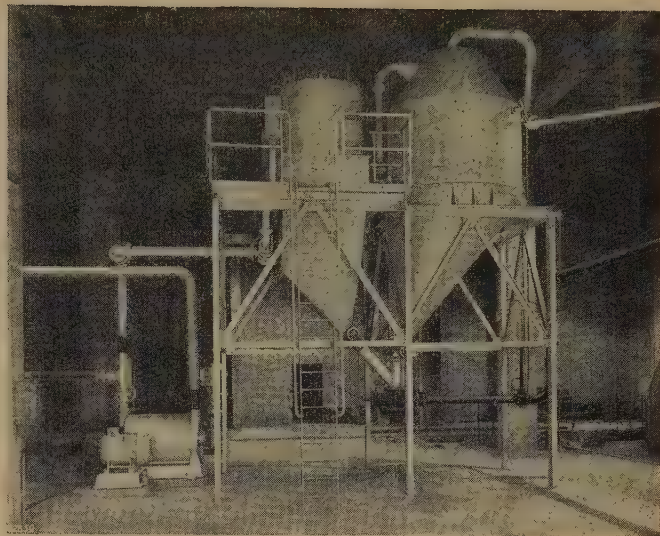
'Araldite' is a registered trade name.

Aero Research Limited *A Ciba Company. Duxford, Cambridge. Telephone: Sawston 2121*

A.P. 264/234

STURTEVANT

Vacuum Cleaning Equipment for Power Stations



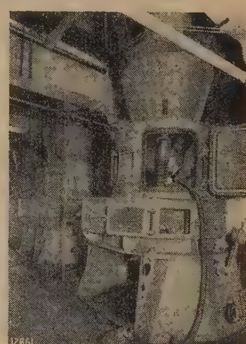
The high standard of cleanliness required in power ations is easily achieved and maintained by Sturtevant quipment, because cleaning can be put on a systematic nd regular basis.

In addition to general cleaning Sturtevant Plant is xtensively applied to flue and boiler cleaning in stoker, .F. and oil-fired boiler plants, and transforms this therwise laborious and objectionable task into a leaner and more effective operation.

Sturtevant Turbo-Exhausters create the very powerful uction required, and the dust collection and settling pparatus in its various forms deals efficiently with all ypes of dust.

A large number of Sturtevant installations are in peration. The illustrations show the plant at a London ower station; surface cleaning; the cleaning of a ulveriser; and emptying the ash pit under a stoker-fired oiler.

lease write to our reference N/101/EB for further particulars



IT'S A GOOD JOB— IT'S STURTEVANT

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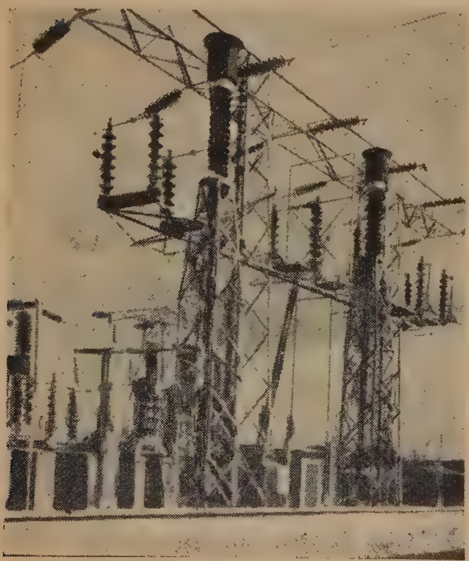

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DISCUSSION ON 'THE MOVING-COIL REGULATOR: A TREATMENT FROM FIRST PRINCIPLES'*

Mr. E. T. Norris (*communicated*): As the inventor of the moving-coil voltage regulator, I welcome the scientific analysis of its operation developed by the authors and agree with the need for it as defined in their Introduction.

Although this treatment from first principles using self- and mutual inductances gives, as the authors have shown, a complete explanation of the regulator performance and is thus intellectually satisfying, it is not practically possible to predict this performance from measurement of the various self- and mutual inductances as separate quantities. These values are all within a few per cent of one another, whereas the regulator performance, as shown by eqns. (5)–(12) and (16)–(22), depends upon differences in pairs of these values, i.e. on small differences between large quantities which themselves are not constant but are affected slightly by saturation.

It is therefore necessary to calculate and measure these differences directly if close agreement between theory and practice is to be obtained. The same problem arises in ordinary transformer work, and for this reason it is the normal practice of transformer engineers to use leakage reactance values between pairs of coils instead of self- and mutual inductances. This is the method employed in the original analysis of the moving-coil voltage regulator given in Reference 1 of the paper.

The reactance, for example, between the two fixed coils a and b is

$$X_{ab} \simeq 2(L_1 - M_1)\omega$$

and this can be measured directly by applying a voltage to one coil with the other short-circuited. Reactances X_{bc} and X_{ac} can be similarly obtained.

Using this method the voltage ratio is derived in formula (9) of Reference 1 as

$$\frac{V_2}{V_1} = \frac{X_{ac} - X_{bc} + X_{ab}}{2X_{ab}}$$

This equation converted as above to self- and mutual inductances becomes, assuming the same number of turns in all three coils,

$$\frac{V_2}{V_1} = \frac{(L_1 - M_1) + (M_2 - M_3)}{2(L_1 - M_1)}$$

The difference between this and the authors' eqn. (10) is practically negligible.

The surprising fact that an output voltage equal to, and even greater than, the input voltage can be obtained is derived in eqn. (12) of the paper. This was shown in the original paper (Section 4) in the form

$$X_{ab} \leqslant X_{bc} - X_{ac}$$

The identity of these two equations is obvious from the foregoing relations.

Although both papers explain this possibility, neither shows how easily it is achieved in practice. The full 100% range is obtained by merely continuing the movement of the moving coil a fraction of an inch past the true concentric position, i.e. exactly level with the fixed coil. By continuing this movement over-ratios of 105% to 110% can be obtained, although 3% is generally the economical limit. Similarly at the other end of the range, values of zero or several per cent negative are possible.

Although the leakage-reactance method as used by engineers satisfies practical requirements and can be reconciled with the authors' classical treatment, it is, in this particular application, technically deficient in not showing any current in the moving coil on no-load. Whilst this current is too small to be of practical consequence, it is scientifically important, as the authors rightly point out in Section 3.1, in that it entirely determines the action of the regulator and causes the unequal distribution of voltage between the two halves of the main winding. It would be difficult to explain how the moving coil could exert any electromagnetic effect unless it carried a finite current, however small. The authors' rigorous analysis, being scientifically complete, includes this characteristic in its comprehensive treatment.

Prof. G. H. Rawcliffe and **Mr. I. R. Smith** (*in reply*): We agree entirely with all Mr. Norris has said, and his comments are much valued. In reply, we might perhaps add a word of history about how the paper came to be written.

Seventeen years ago, when a moving-coil voltage regulator was being installed in the University of Liverpool, a senior student was reading Mr. Norris's original paper (Reference 1 of our paper) on the subject. It contains these words: 'The current in the short-circuited coil for any regulator position is zero at no-load.' The student commented that this could not be true; since, if it were, the coil might just as well not be there. He was, of course, quite right. Since then, at intervals, several practising engineers and other students have asked one of us (G. H. R.) other questions about the regulator; such as why the short-circuited coil does not carry a huge current, as it would in a transformer. We have much enjoyed preparing what is, in effect, an answer to these questions, and we are very grateful for Mr. Norris's sympathetic interest in our work.

* RAWCLIFFE, G. H., and SMITH, I. R.: Paper No. 2203 S, February, 1957 (see 104 A, p. 68).

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Paper No. 2334 S
June 1957

TRANSISTOR VOLTAGE REGULATORS FOR ALTERNATORS

By E. E. WARD, Ph.D., Associate Member, and N. H. SABAH, M.Sc., Student.

(*The paper was received* 12*th October*, 1956.)

SUMMARY

The paper is concerned with alternator voltage regulators in which a junction transistor regulates the field current of a self-excited exciter. It examines the principles upon which control circuits may be designed to ensure stability and gives experimental results on two regulating systems for a 10 kVA alternator.

LIST OF SYMBOLS

A_1, A_2, A_3 = Numerical gain factors.
I, i = Input current of transistor A.
I_1, i_1 = Exciter shunt field current.
I_2, i_2 = Control current.
I_{c0} = Collector current at zero emitter current.
k = dV/dI_1.
L = Exciter shunt field inductance.
R_0 = Output resistance of transistor A.
R_1 = Resistance of exciter shunt field winding.
R_2 = Potentiometer arm, positive end.
R_3 = Potentiometer arm, negative end.
R_4 = Internal resistance of control source.
a, r_b, r_c, r_e, r_m = Parameters of transistor equivalent circuit.
T_1, T_2, T_3 = Time-constants.
V, v = Exciter terminal voltage.
V_1, v_1 = Output voltage of transistor A.
V_2, v_2 = Input voltage of transistor A.
V_{2A} = Voltage across R_2 when transistor is disconnected from point A.
V_3 = Control source e.m.f.
V_4 = Constant polarizing e.m.f.
V_5 = Input voltage of transistor B.

(1) INTRODUCTION

Alternators of outputs less than 500 kW are usually excited by a self-excited d.c. generator, and the automatic voltage regulator is connected in series with the exciter shunt field circuit. The regulating elements which are at present in use for this purpose include mechanically variable resistances, and magnetic or electronic amplifiers. The present paper shows how regulation may be obtained by connecting a junction transistor in the exciter field circuit. Such a regulator dispenses with moving mechanical parts without resorting to thermionic valves; it can offer high amplification and therefore small error; the high output resistance which may be realized with a transistor can improve the exciter response and will allow the exciter voltage to be regulated down to its remanent-magnetism value; if silicon transistors are used the regulator will work over a great range of temperature, and it is expected that the present rate of development in transistor manufacture will result in elements of long life and low cost.

Measurements have been made on two different transistor regulators and have led to a theory of the behaviour of self-excited d.c. generators when regulated by a junction transistor. The conclusions of this theory may be applied tentatively to alternators which are self-excited by means of a rectifier. Investigations have been restricted to direct-acting error-operated regulators wherein the error of output voltage is always finite and is reduced to within acceptable limits by the increase as necessary of the amplification in the control system.

It will be seen that the regulators described in the paper must have two kinds of stability. One kind means that the regulator is free from the continuous oscillations which occur if it does not meet the Nyquist criterion for their prevention; since such oscillations are associated with inductive or capacitive energy-storage this kind of stability will be called 'dynamic stability'. The other kind of stability refers to a non-linear circuit where only direct currents and voltages occur, and means that the circuit will always return to its quiescent point after a displacement and that only one such point exists; this will be called 'd.c. stability'. It is well known that a self-excited generator loses its d.c. stability if the field circuit resistance exceeds a critical value, and this effect appears in some form or another in all the circuits examined below since they are all supplied from the variable potential across the exciter brushes. It is therefore essential to achieve d.c. stability with the regulator control loop open, and the necessary means will be examined in detail.

All the circuits which will be examined may be represented by Fig. 1, where the transistor is connected in series with the field winding.

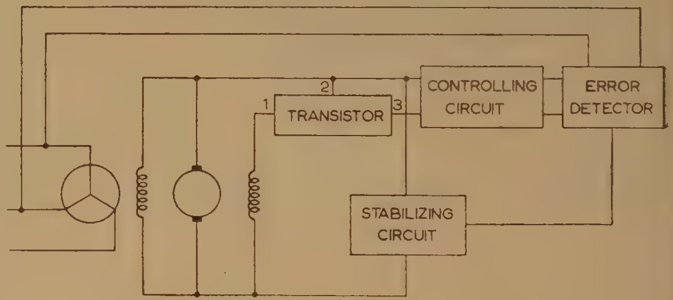

Fig. 1.—Block diagram of regulator.

The alternative in which the transistor is connected as a diverter in shunt with the field winding has been investigated briefly and does not appear to offer any practical advantages. The exciter field circuit and its series transistor as shown in Fig. 1 will be called the 'regulating circuit', and the networks conveying the signal from the error detector to the regulating transistor will be called the 'control circuit'.

(2) REGULATING CIRCUITS

Referring to Fig. 1, transistor terminal 1 may be any one of the three electrodes; in each case there are two ways of connecting terminals 2 and 3. There are therefore six ways of connecting the transistor; they are known by the electrode connected to terminal 2 which is the terminal common to both input and output circuits.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Dr. Ward is, and Mr. Sabah was, in the Electrical Engineering Department, University of Birmingham.

Of these six circuits the two wherein terminal 3 is the collector and the third wherein 2 is the collector and 3 the emitter have little practical application. Attention has therefore been restricted to the common-base circuit with emitter control, the common-emitter circuit with base control, and the common-collector circuit with base control.

(2.1) Matching of Exciter and Transistor

The characteristics of the machines and transistors which have been used in experiments are given in Sections 8.1 and 8.2, and the excitation characteristics of the loaded exciter are shown in Fig. 2 for both rising and falling excitation as measured both

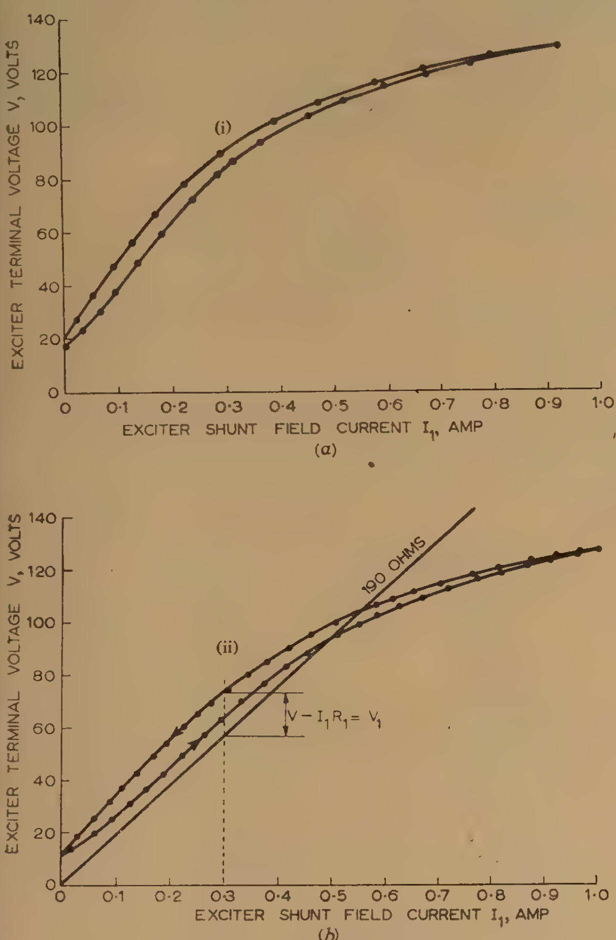

Fig. 2.—Excitation curves.
(*a*) With positive compounding.
(*b*) Without compounding.

(*a*) with and (*b*) without cumulative compounding. These characteristics are shown in Fig. 3 superimposed on a family of curves which define the performance of the field circuit; they show the relation of field current to the sum of the field-winding potential drop and the transistor output voltage in common-emitter connection; base current is the constant parameter for each curve. For any given base current the machine therefore operates at the intersection of the appropriate field-circuit curve with the rising or falling excitation curve.

For design purposes, however, it is more convenient to use curves relating transistor output current and voltage. Referring to Fig. 2, where the straight line indicates the potential drop across the field coil, the transistor output voltage at a given field current is the intercept between this line and the excitation curve.

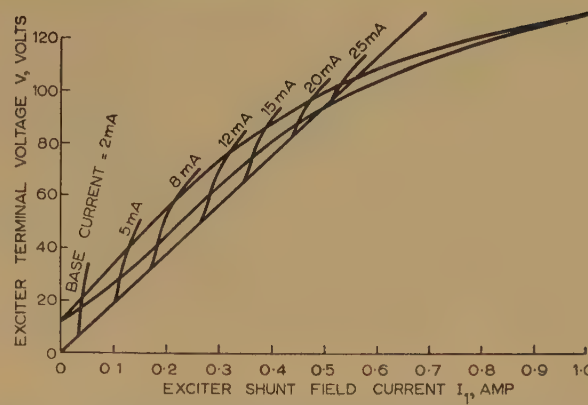

Fig. 3.—Excitation curve with characteristics of transistor and field circuit.

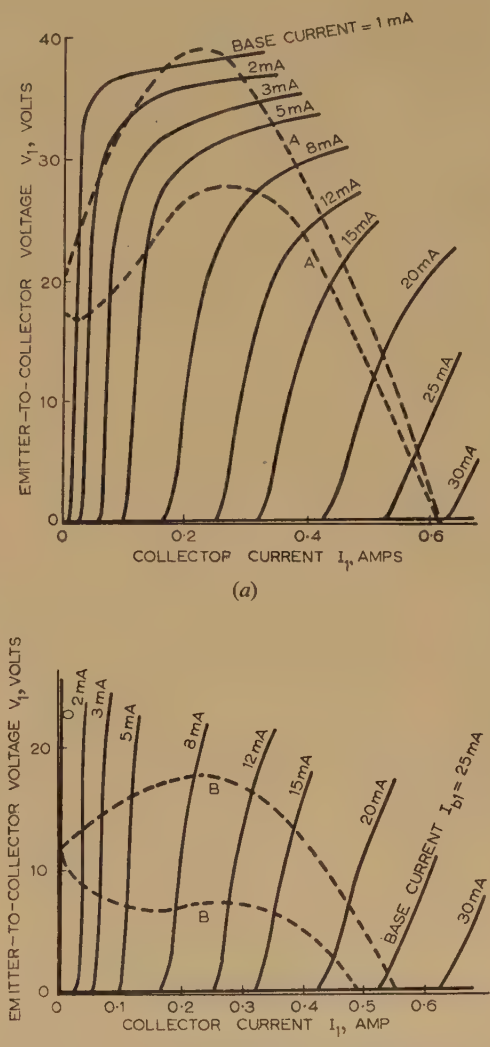

Fig. 4.—Transistor common-emitter curves and load lines.
(*a*) With positive compounding.
(*b*) Without compounding.

This transistor output voltage is plotted as a function of field current, i.e. transistor output current, in Fig. 4, where it is shown in a broken line which may be called the load line of the transistor.

Thus the performance of the circuit in common-emitter, -base or -collector arrangements may be found by superimposing the broken curve on the appropriate set of characteristics. This is shown in Fig. 4 for the common-emitter connection. This diagram is the most convenient means for co-ordinating the characteristics of exciter and transistor. In particular, it will be seen later that difficulties arise if the transistor load line is allowed to leave the zone of linear operation as on curve A of Fig. 4 at high collector voltages; in this region the transistor collector resistance falls, and the load line may become parallel to the transistor curve so that d.c. stability is lost. Curve B of the same Figure, corresponding to excitation curve (ii) in Fig. 2, falls in a more nearly linear region for the transistor and avoids this danger.

(2.2) The Regulating Characteristic

The regulating curve giving commutator voltage as a function of current entering at terminal 3 of Fig. 1, may be found for common-emitter connection from Figs. 2 and 4; the measured curve is plotted in Fig. 5; for the common-collector circuit the curve differs only slightly from Fig. 5; for the common-base circuit the curve differs only slightly from the excitation curve in Fig. 2.

The curves in Fig. 5 show the result of operating the transistor outside the linear region of its characteristic curves; curve (i), which corresponds to those labelled (i) in Figs. 2 and A in 4, shows that the given transistor is not suitable in common-emitter connection for controlling a machine having the excitation curve (i) of Fig. 2; stable control is, however, possible for a machine giving the curves labelled (ii). Fig. 5 also shows that there may be considerable differences between the curves for rising and falling excitation, and reference back to Fig. 3 confirms that these differences will be reduced if the output resistance of the transistor is high. It is also clear from Fig. 3 that the crowding together of the constant base-current curves at high values of field current contributes noticeably to the saturation of the regulating characteristic which is seen in Fig. 5.

(2.3) The Input Characteristic

For the design of the control circuits feeding the regulating transistor, and in particular for investigations of the d.c. stability of the system, it is necessary to know the relation of direct current and voltage at the points where control is applied; these are terminals 2 and 3 in Fig. 1. For common-emitter connection the measured relation is shown in Fig. 6; it may be derived from Fig. 4, given the common-emitter input characteristics; for common-base connection the relation is very similar, but the control current is on a much larger scale. For common-collector connection the input current and voltage as measured are shown in Fig. 6; since the emitter-to-base potential is small and the field current is roughly proportional to the base current, these curves have the general shape of the load lines shown in Fig. 4. The portions PQ and RS in Fig. 6 represent negative resistance and could lead to d.c. instability.

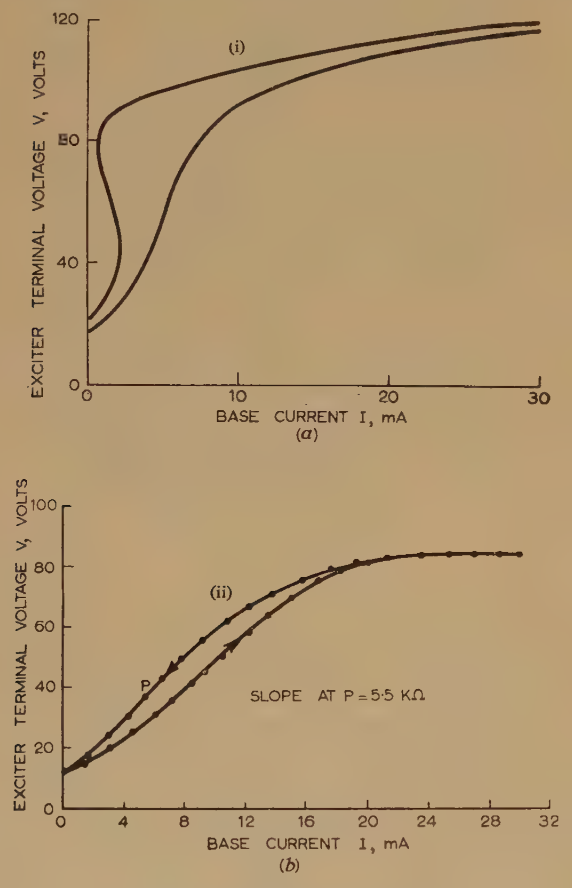

Fig. 5.—Regulating characteristic.

(a) With positive compounding.
(b) Without compounding.

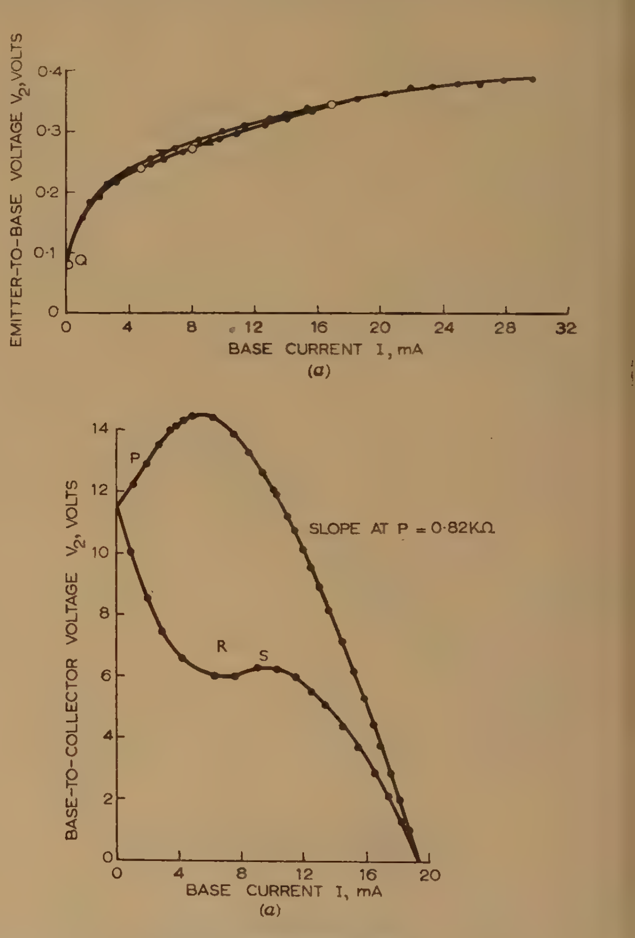

Fig. 6.—Input characteristic.

(a) Common-emitter regulating circuit.
(b) Common-collector regulating circuit.

(2.4) Comparison of Transistor Configurations

For a regulator designed on the general plan shown in Fig. 1, the common-base connection suffers the serious disadvantage of giving no current amplification. The common-collector circuit gives large current amplification, but its input characteristic, given in Fig. 6, shows that it must be supplied from a high-resistance source to preserve d.c. stability. It is therefore attractive as a means of manual control from a low-power rheostat, but for automatic regulation its low output impedance leads to poor dynamic performance. The common-emitter circuit is therefore best for automatic regulation; its output impedance is seen from Fig. 4 to be high enough within the linear range for useful practical application, though not as high as in the common-base circuit; its input voltage and current are small and are related by a simple monotonic function as shown in Fig. 6; finally, the circuit lends itself to the addition of negative feedback, by which its output impedance may be increased.

(3) DESIGN OF CONTROL CIRCUITS

(3.1) Functions of the Control Circuit

The functions of the control circuit are:

(*a*) To transmit the error signal from the error detector to the regulating transistor and to provide any amplification which may be needed to keep the finite voltage error within the acceptable limits.

(*b*) To provide such input conditions for the regulating circuit as will ensure d.c. stability when the control loop is open.

(*c*) To provide such dynamic properties in the closed control loop as will ensure dynamic stability and give fast operation; a further stabilizing circuit may be added to improve these properties.

(*d*) To provide, if required, some protection against the reversal of polarity of the exciter.

(*e*) To provide full exciter output if the sampling signal vanishes owing to a short-circuit of the alternator. This may be done in three ways:

(i) A supplementary control signal may be derived from current transformers in the alternator output leads. The other arrangements described below are simpler in practice.

(ii) Special elements may be added to the control circuit which function only on alternator short-circuit to increase the excitation to its maximum.

(iii) The control circuit may be designed so that it inherently takes up the condition of maximum excitation when the sampling signal vanishes.

To perform these functions two circuits have been used and will be analysed below; the potentiometer circuit inherently gives full excitation in the absence of the sampling signal and will be examined in detail, since the second circuit is a special instance of it; the resistance control circuit needs additional elements to provide full excitation on short-circuit, but it has certain important advantages.

(3.2) Potentiometer Control Circuit

This circuit is shown in Fig. 7 for a *p-n-p* transistor whose terminal 1 is the collector, 2 is the emitter and 3 the base; the error detector or some amplifier of its signal produces a direct voltage V_3 in a circuit of internal resistance R_4 resulting in a control current I_2 which flows into the tapped point of the potentiometer. This circuit is analysed in Section 8.3, where it is shown that for a fixed value of V_3 the d.c. stability is ensured provided that the following inequality is satisfied:

$$\frac{dV_2}{dI}\left[1+\frac{R_2R_3}{R_4(R_2+R_3)}\right] > \frac{R_2}{R_2+R_3}\left(\frac{dV}{dI}-R_3\right) \qquad (1)$$

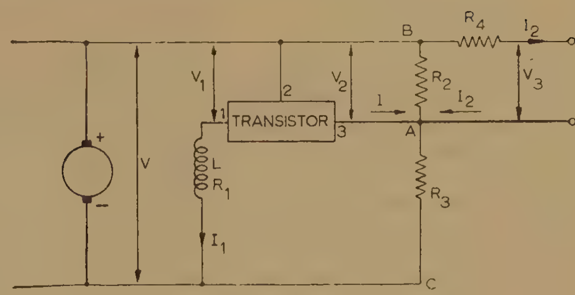

Fig. 7.—General control circuit.

Figs. 5 and 6 show that for common-emitter connection both the above differential coefficients may be always positive if the transistor is working in its linear region. The circuit is therefore stable if the right-hand side of the inequality is always negative, i.e. if R_3 is greater than the maximum value of dV/dI. If R_3 does not meet this condition the circuit may still be stable if the left-hand side of the inequality exceeds the right-hand side in magnitude, and this may always be ensured by making the source resistance R_4 sufficiently small.

The above criterion of stability means in practical terms that the control circuit may be designed in one of three ways:

(*a*) R_3 may be made larger than the maximum value of dV/dI, which in Fig. 5 occurs at point P, and in this case the source resistance R_4 may have any positive value. The result is that at zero error when $I_2 = 0$ the operating point is well down the control curve and the machine delivers only a fraction of its full output voltage. The upper portion of the control curve can only be reached if the error detector can provide a current I_2 of reversible polarity; this requirement leads to a complicated circuit since the error detector output must in general be passed through a transistor amplifier in order to provide acceptable sensitivity. This arrangement has therefore not been used.

(*b*) R_3 may again be given a large value as above, and a source of direct potential may be connected in series with it so that when $I_2 = 0$ the operating point is at the top of the control curve giving full excitation. R_4 may still have any value. Stable operation will result and I_2 need not now reverse in sign, but the circuit does not provide full excitation on short-circuit unless the direct potential is provided by some source such as a battery which is unaffected by the busbar voltage.

(*c*) R_2 and R_3 may be chosen so that when I_2 vanishes full excitation occurs. The resulting value of R_3 is now too low for stability unless R_4 is made small. Fig. 8 shows the measured curve relating I_2 and V_2 for rising and falling excitations; to ensure d.c. stability the value of R_4 must not exceed the minimum positive slope of this curve, which is of the order of 25 ohms.

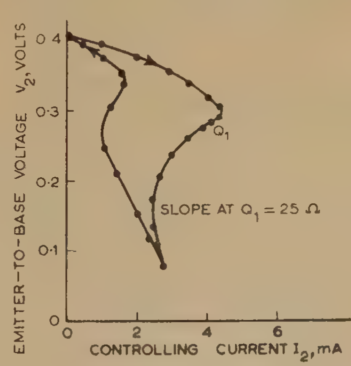

Fig. 8.—Input characteristic of potentiometer.

If R_2, R_3 and R_4 are chosen in this way the circuit meets all the above requirements.[11]

Circuit (*b*), in which a source of potential is added in series with R_3, has not been used in practice; however, if in this circuit R_2 is made infinite, valuable properties appear; the arrangement is examined fully in Section 3.3. Thus circuit (*c*) is preferred as the basis of a regulator; it leads to a simple design, and, as is shown in Appendix 8.4, the low source resistance which it requires is favourable to the use of series feedback to increase the transistor output resistance. This low source resistance has been obtained by using a small amplifying transistor in common-collector connection having an output resistance of a few ohms; the base of this transistor is fed directly from the error detector. The voltage/current relation at the base is not a monotonic function but is roughly a replica of the curve in Fig. 8, although the slopes are increased by a factor roughly equal to the current amplification of the transistor. It follows, therefore, that the precautions needed to secure d.c. stability when feeding a control signal to point A of the potentiometer are equally necessary when feeding the base of the amplifying transistor, but with the difference that the critical minimum value of source resistance (in this case, of the error detector network) is now roughly 2000 ohms. Fig. 9 shows the measured exciter terminal voltage as a function of the base-to-collector voltage of the amplifying transistor.

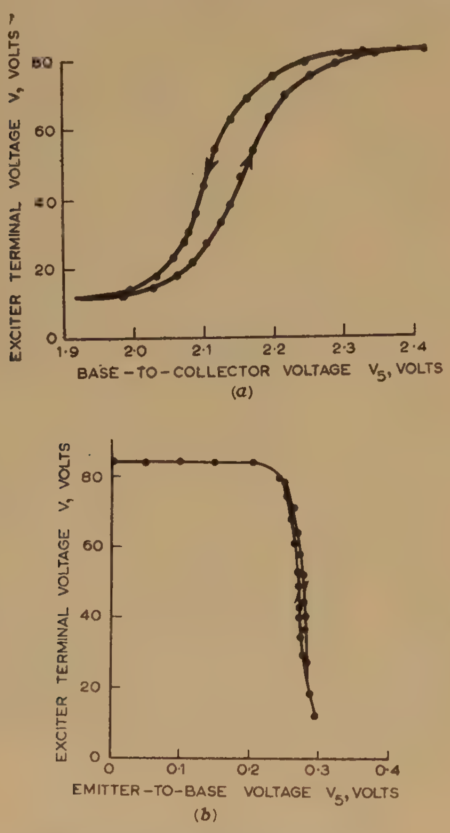

Fig. 9.—Excitation characteristics.

(*a*) Potentiometer control circuit.
(*b*) Resistance control circuit.

(3.3) Resistance Control Circuit

This circuit is also a common-emitter connection and may be represented by Fig. 7 if transistor terminal 3 again represents the base, resistor R_2 is infinite, and a source of constant e.m.f. is connected in series with R_3. The circuit may be regarded as a positive-feedback arrangement in which resistor R_3 has the effect of increasing both the control sensitivity and the input resistance. It may alternatively be thought of as a special case of the potentiometer circuit, and since the appropriate analysis has already been developed in Appendix 8.3, this viewpoint will be taken. The criterion for d.c. stability is given by making R_2 infinite in relation (1) and is therefore

$$\frac{dV_2}{dI}\left(1 + \frac{R_3}{R_4}\right) > \left(\frac{dV}{dI} - R_3\right) \quad . \quad . \quad . \quad . \quad (2)$$

The resulting requirements are the same as those placed on the potentiometer circuit, namely either that R_4 must be small or that R_3 must exceed the greatest value of dV/dI. It is this second arrangement which is of particular practical interest; since it may be controlled from a high-resistance source, an amplifying transistor in common-emitter connection may be used to supply the control signal; moreover, it will be seen from Section 8.5 that, if R_3 does not greatly exceed the maximum value of dV/dI, the full range of excitation may be controlled by only a small change in I_2; these factors lead to a high control sensitivity. The provision of the constant e.m.f. in series with R_3 will be discussed below.

The input resistance as seen by the error detector is that of the emitter-to-base path of the amplifying transistor and varies in the region of hundreds of ohms; the relation of current to voltage is a simple monotonic function, and d.c. stability is assured whatever the output resistance of the error detector. The measured exciter terminal voltage is shown in Fig. 9 as a function of the emitter-to-base voltage of the amplifying transistor.

(4) THE COMPLETE REGULATOR

Two regulators have been built and tested according to the above principles; Fig. 10 shows a system using the potentiometer control circuit, and Fig. 11 the resistance control circuit. In each case the regulating transistor is labelled A and the amplifier B; a 3-phase rectifier has been used to feed the error detector in order to reduce the time-constant of the smoothing circuit and gives a ripple voltage of the order of 0·4 volt (d.a.p.) across the smoothing capacitor; on account of the large amplification following the error detector larger ripple voltages could not be accepted; the direct potential across this capacitor is about 150 volts. The potentiometers R_5 are used for setting the no-load

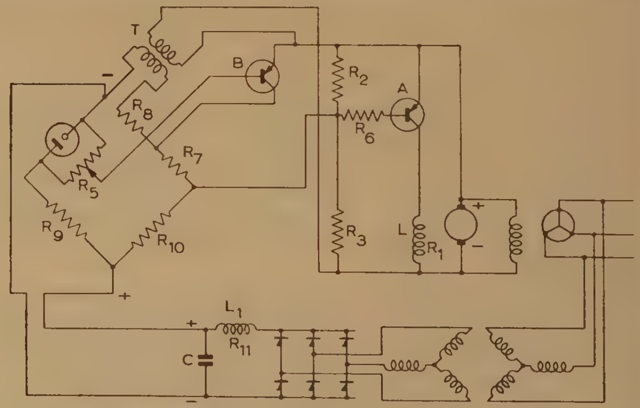

Fig. 10.—Complete regulator: potentiometer control.

R_2	500 Ω.	R_9	2 200 Ω.
R_3	4 kΩ.	R_{10}	600 Ω.
R_5	10 kΩ.	R_{11}	11 Ω.
R_6	1 kΩ.	L_1	3 H.
R_7	25 Ω.	C	8 μF.
R_8	1 300 Ω.		

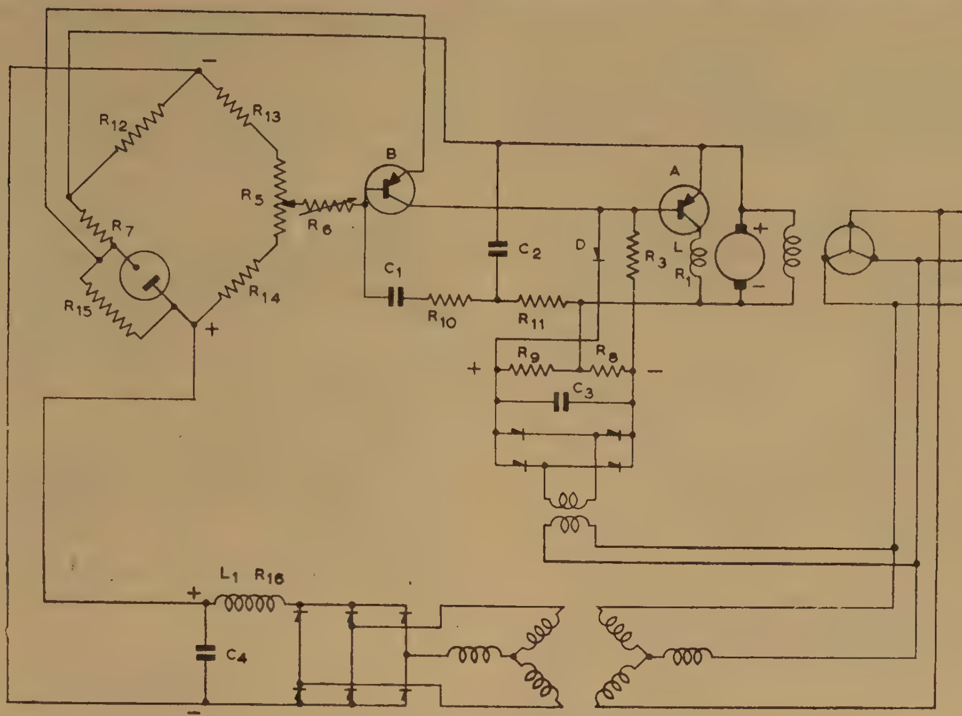

Fig. 11.—Complete regulator: resistance control.

R_3	6900 Ω.	R_{13}	1200 Ω.
R_5	1 kΩ.	R_{14}	2400 Ω.
R_6	5 kΩ.	R_{15}	6600 Ω.
R_7	100 Ω.	R_{16}	11 Ω.
R_8	8 kΩ.	L_1	3 H.
R_9	2400 Ω.	C_1	4 μF.
R_{10}	4300 Ω.	C_2	1 μF.
R_{11}	38 kΩ.	C_3	40 μF.
R_{12}	1500 Ω.		

alternator voltage, and the resistances R_6 vary the sensitivity of the regulator.

In Fig. 11 the constant e.m.f. in series with resistor R_3 is provided by the single-phase bridge rectifier which feeds the potentiometer R_8, R_9; the required constant e.m.f. appears across resistor R_8, and will be proportional to the regulated alternator output voltage, so that its variation over the range of load is small. However, this arrangement by itself cannot provide full excitation on short-circuit, since the output of the rectifier vanishes under these conditions. The difficulty is overcome by a diode-clamp circuit[10] consisting of the diode D polarized by the potential across resistor R_9; the diode is a small metal-plate rectifier which is unable to conduct so long as the busbar voltage is near to its normal regulated value; on short-circuit, however, the polarizing potential of the diode clamp vanishes and connects the base of transistor A to the negative line through resistor R_9, which is chosen so that in conjunction with R_3 and R_8 it affords full exciter output. This arrangement has given satisfactory operation on the test-bed over a considerable period.

(4.1) The Error Detector

No detailed examination of error detectors has been made, but a general review shows that a bridge circuit including a glow-discharge tube gives greater sensitivity than the other types available; for laboratory investigations therefore this type has been used.

For the circuit in Fig. 10 the source resistance seen by transistor B must be low, and this has been achieved by the component values given; the maximum source resistance compatible with d.c. stability is of the order of 2 kilohms. In Fig. 11 the output resistance of the error detector may have any value, and this freedom has been used to control the overall sensitivity by the series resistor R_6. The above considerations affecting the design of the error detector are slightly modified by the addition of resistor R_7, which is added to provide collector polarizing potentials for the transistor B. The sensitivity of the error detector could be increased and its output impedance reduced by adding a second glow tube in the bridge circuit.

(4.2) Comparison of the Two Regulators

(4.2.1) Accuracy of Regulation.

For reasons already explained, the amplification available in the resistance control regulator of Fig. 11 is considerably greater than that of Fig. 10, so that the voltage regulation is much better; the measured fall of busbar voltage on suddenly applying full load of 10 kVA at 0·80 lagging power factor is about 1·4 volts for the circuit of Fig. 10 and 0·3 volt for that of Fig. 11.

(4.2.2) Dynamic Performance.

The transfer function of the regulating circuit in combination with each of the two control circuits is derived in Section 8.5. It has already been shown that the resistance control circuit can give sensitivities increasing indefinitely if R_3 only slightly exceeds the maximum value of dV/dI; the equality of these quantities gives the boundary of d.c. stability, and it will be shown in Section 8.5 that the time-constant of the combined regulating and control circuits becomes infinite as this equality is approached. Further, if the greater electronic amplification possible with the resistance control circuit is in fact utilized, it will be necessary to precede the error detector by more thorough filtering than with the potentiometer circuit; the filter time-constant will therefore be greater. For both these reasons, therefore, the

regulator of Fig. 11 is the slower of the two in transient response, although giving greater precision of regulation. It is stabilized by the network R_{10}, R_{11}, C_1, C_2. The Nyquist diagram, as measured by breaking the control loop between the error detector and its supply filter with the addition of the necessary terminations on both sides, is shown in Fig. 12, before and after stabilization.

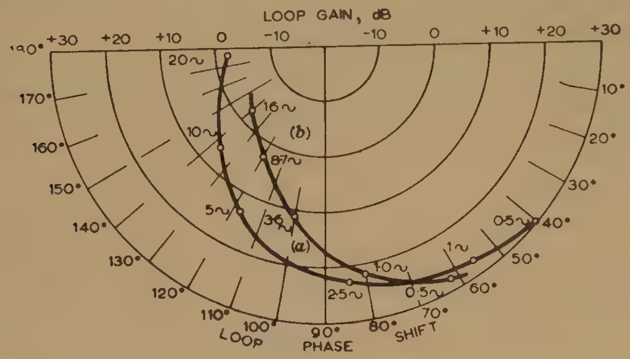

Fig. 12.—Nyquist diagram for resistance control regulator.

(a) Without stabilizing network.
(b) With stabilizing network.

In the regulator shown in Fig. 10 the regulating transistor A is in common-emitter connection and controlled from a low-resistance source; its output resistance is therefore high, resulting in a small time-constant of the exciter field circuit. Since transistor B in common-collector connection has no voltage amplification, considerable ripple voltages may be tolerated at the output of the error detector, and the time-constant of the smoothing circuit may be small. This circuit is therefore the better adapted of the two to applications calling for fast transient response. With the circuit values given in the Figure and without the addition of the stabilizing transformer T, the loop phase margin was measured to be 40°.

On account of this satisfactory phase-margin it has been possible to dispense with this stabilizing transformer; if it is necessary its output winding should be connected so that a large fraction of its induced e.m.f. will appear between collector and base of transistor B, but it is better to avoid inserting this winding directly in the base lead of the transistor, since this would increase the effective output resistance of the transistor. The connection shown in Fig. 10 is therefore preferred when the transformer has to be used.

(5) CONCLUSIONS

The investigations described have shown that regulators of high performance may be built using the junction transistor as a regulating element, and have outlined the principles on which their design should be based.

(6) ACKNOWLEDGMENTS

The work described was carried out in the Electrical Engineering Department of the University of Birmingham and the authors wish to acknowledge their indebtedness to Professor D. G. Tucker for his support and encouragement, and for making available the facilities of the Department.

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(8) APPENDICES

(8.1) Characteristics of Test Machines

(a) Alternator

Revolving-armature alternator, 10 kVA, 0·8 power factor, 230 volts, 25·1 amp, 50 c/s, 3-phase, 1 500 r.p.m. with damping winding.
Field resistance: cold, 19·15 ohms; hot, 24 ohms.
Field current at full load, 0·8 power factor: 4·5 amp.
Fall in voltage on applying full load: 17%.

(b) Exciter

6 amp 110-volt 3 000 r.p.m. (cumulative compounding disconnected).
Field resistance: cold, 153 ohms; hot, 190 ohms.

(8.2) Characteristics of Transistors

(a) Regulating Transistor A

Absolute maximum ratings:

Collector voltage ..	.. 60 volts.
Collector current ..	.. 4 amp.
Dissipation at 25° C	.. 15 watts.

(b) Amplifying Transistor B

Absolute maximum ratings:

Collector voltage ..	.. 13 volts
Collector current ..	.. 110 mA
Dissipation at 60° C	.. 45 mW

(8.3) Analysis of Control Circuit

(8.3.1) General Relations.

The regulating and control circuits together with the symbols used are shown in general form in Fig. 7. In the steady state the conditions in the regulating circuit may be written as:

$$V = f_1(I_1) \quad (3)$$

$$V = V_1 + I_1R_1 \quad (4)$$

$$V_1 = f_2(I, I_1) \quad (5)$$

$$V_2 = f_3(I, I_1) \quad (6)$$

The regulating characteristic is the relation

$$V = f_4(I) \quad (7)$$

and the input characteristic of electrode 3 of the transistor is the relation

$$V_2 = f_5(I) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Eqns. (3), (5) and (6) have been obtained by experimental measurement; eqns. (7) and (8) may be derived from them and have been confirmed by measurement.

(8.3.2) **Criterion for D.C. Stability.**

The electrode 3 of the transistor is normally controlled from point A of the potentiometer R_2, R_3, but in order to explore the working of this arrangement it is convenient to disconnect terminal 3 from point A and to imagine a current I flowing into the point A from an external source, and at the same time an equal current I flowing out at terminal 3. If, under these conditions, the potential across R_2 is V_{2A}, then by the superposition theorem

$$V_{2A} = V\frac{R_2}{R_2 + R_3} - (I + I_2)\left(\frac{R_2R_3}{R_2 + R_3}\right) \quad . \quad . \quad (9)$$

and for the source of signal

$$V_{2A} = V_3 + I_2R_4 \quad . \quad . \quad . \quad . \quad (10)$$

giving

$$V_{2A} = \frac{V - IR_3 + \dfrac{V_3R_3}{R_4}}{\dfrac{R_3}{R_4} + \dfrac{R_2 + R_3}{R_2}}$$

If the currents entering at A and leaving at terminal 3 are now increased by δI while V_3 remains constant, the condition for stability is that

$$\delta V_2 > \delta V_{2A}$$

These increments are

$$\delta V_2 = \delta I\frac{dV_2}{dI}$$

$$\delta V_{2A} = \delta I\frac{dV_{2A}}{dI}$$

$$= \delta I\frac{dV/dI - R_3}{\dfrac{R_3}{R_4} + \dfrac{R_2 + R_3}{R_2}}$$

and therefore d.c. stability will be obtained if

$$\frac{dV_2}{dI} > \frac{(dV/dI) - R_3}{\dfrac{R_3}{R_4} + \dfrac{R_2 + R_3}{R_2}} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

(8.3.3) **Potentiometer Control Characteristics.**

In order to predict the control current I_2 needed to produce a given voltage V when the potentiometer circuit is in operation as a regulator, V_{2A} is equated to V_2 and eqns. (7), (8) and (9) are solved simultaneously. To arrive at such a solution eqn. (9) is written in the form

$$(V - IR_3) - I_2R_3 = V_2\left(1 + \frac{R_3}{R_2}\right) \quad . \quad . \quad . \quad (12)$$

The experimental values of $(V - IR_3)$ for a given value of R_3 may be taken from eqns. (7) and (8); both these quantities may be plotted as functions of V_2 as shown in Fig. 13, where $R_3 = 7000$ ohms, and Fig. 14, where $R_3 = 4000$ ohms. Then for a given value of $(V - IR_3)$ the intercept PQ between the curve and the straight line representing eqn. (12) gives the

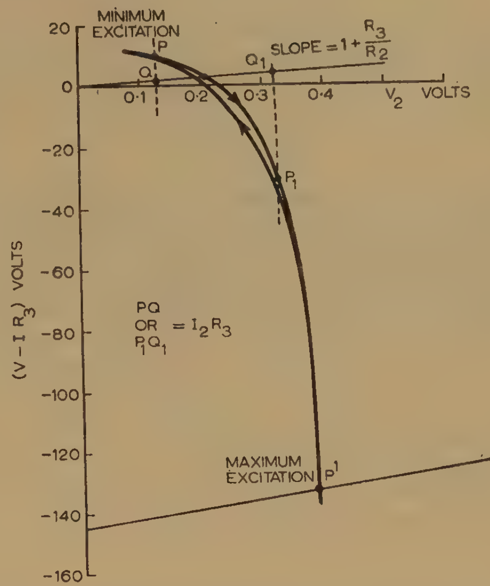

Fig. 13.—Graphical determination of control current for potentiometer control: $R_3 = 7\,\text{k}\Omega$.

difference I_2R_3. Fig. 14 applies to the complete regulator shown in Fig. 10.

Thus, to predict the control current I_2 corresponding to a given value of V, the appropriate value of I is obtained from the experimental curve of eqn. (7) as plotted in Fig. 5, and the difference $(V - IR_3)$ is entered as an ordinate on Fig. 14, thus

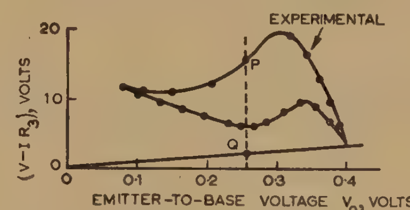

Fig. 14.—Graphical determination of control current for potentiometer control: $R_3 = 4\,\text{k}\Omega$.

giving the intercept PQ and the value of I_2. The relation of V and I_2 derived from Fig. 14 is not a monotonic function, and the d.c. stability would be conditional upon using a low-resistance control source. (These results are to be expected, since for these curves R_3 does not exceed the maximum value of dV/dI as required for unconditional stability.) Fig. 13 represents a circuit which has d.c. stability for all values of source impedance, since R_3 always exceeds dV/dI, and confirms that when I_2 is zero the operating point is at a low value of excitation, so that I_2 must be reversed in sign to reach the maximum excitation.

(8.3.4) **Resistance Control Characteristics.**

For the resistance control circuit a similar construction may be used. V_{2A} is obtained by making R_2 infinite in eqn. (9), giving

$$V_2 = V_{2A} = V - (I + I_2)R_3 \quad . \quad . \quad . \quad (13)$$

If now a source of constant e.m.f. V_4 is connected in series with R_3, then V_2 becomes

$$V_2 = V - (I + I_2)R_3 + V_4$$

or $$(V - V_2) - I_2R_3 = IR_3 - V_4 \quad . \quad . \quad (14)$$

The voltage between the negative brush and terminal 3 of the transistor is $(V - V_2)$ and may be written

$$(V - V_2) = f_6(I) \quad . \quad . \quad . \quad . \quad (15)$$

Then the operating point is found by solving simultaneously eqns. (14) and (15). The voltage V_2 is the emitter-to-base voltage of the transistor, and for the sample used did not exceed 0·5 volt; for 100-volt machines, therefore, the difference between eqns. (7) and (15) is negligible.

Eqns. (14) and (15) may be solved by the graphical construction shown in Fig. 15, where the measured values of $(V - V_2)$

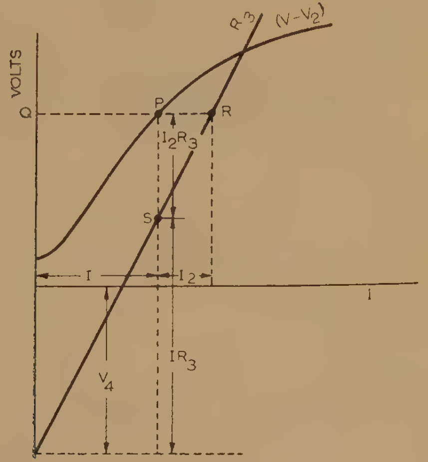

Fig. 15.—Graphical determination of control current for resistance control.

and the difference $(IR_3 - V_4)$ are plotted as functions of I. At a given operating point P, the intercept PS represents the difference I_2R_3 and PR represents I_2, so that PQ represents I.

(8.4) Exciter Field Time-Constant

If in Fig. 7 a generator of small sinusoidal voltage δV is connected in series with terminal 1 of the transistor, thereby causing an alternating current δI_1 to flow in the field circuit and a variation $k\delta I_1$ in the armature induced e.m.f., then

$$\delta V + k\delta I_1 = \delta I_1(R_1 + R_0 + pL)$$

where R_0 is the output resistance of the transistor and $k = dV/dI_1$. From this relation

$$\delta I_1 = \frac{\delta V}{pL + R_1 - k + R_0}$$

showing that the effective time-constant of the field circuit is

$$\frac{pL}{R_1 + R_0 - k}$$

If R_0 is very small, this time-constant may rise to large values if dV/dI_1 at the operating point is only slightly less than R_1. The time-constant is reduced in the familiar manner for large values of R_0. The common-collector, common-emitter and common-base transistor configurations have output impedances in ascending order. However, if in the common-emitter connection, a feedback resistor is inserted in the emitter lead and the base is fed from a low-resistance source, the circuit has an output impedance which may approach that of the common-base configuration.

(8.5) Transfer Function of Control Circuit

An equivalent circuit for the regulating transistor in common-emitter connection and the control circuit is given in Fig. 16,

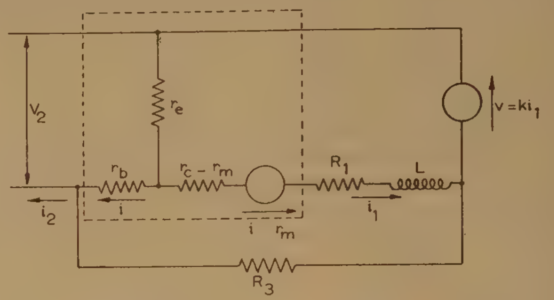

Fig. 16.—Equivalent circuit of transistor and exciter.

together with the symbols to be used. The elements within the dotted rectangle represent the transistor; the analysis will assume small displacements over which the system may be assumed to be linear. The resistance R_2 has been omitted from the equivalent circuit, since it is not used in the resistance control circuit and in the potentiometer control circuit its effect in shunt with the low-resistance control source is very small; the internal impedance of the exciter armature will be assumed to be negligible.

The following transfer functions may be derived from the equivalent circuit:

$$\frac{v}{v_2} = \frac{A_1}{1 + pT_1} \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where

$$A_1 = \frac{k(r_m - r_e)}{(R_1 - k + r_c)(r_e + r_b) - r_b(r_m - r_e)}$$

$$\simeq \frac{ka}{r_e + r_b(1 - a)}$$

$$a = r_m/r_c$$

$$T_1 = \frac{L}{R_1 - k + r_c(1 - a) + ar_c\left(\frac{r_e}{r_e + r_b}\right) + \frac{r_e r_b}{r_e + r_b}}$$

$$\frac{v}{i} = \frac{kA_2}{1 + pT_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

where $$A_2 = \frac{r_m - r_e}{R_1 - k + r_c - r_m + r_e}$$

$$\simeq \frac{a}{1 - a}$$

$$T_2 = \frac{L}{R_1 - k + r_c(1 - a) + r_e}$$

$$\frac{v}{i_2} = \frac{kA_3}{1 + pT_3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

where $$A_3 = \frac{A_2}{1 - \frac{kA_2}{R_3}\left(1 - \frac{1}{A_1}\right)}$$

$$\simeq \frac{A_2R_3}{R_3 - kA_2} \qquad A_1 \gg 1$$

$$T_3 = A_3\left(\frac{T_2}{A_2} + \frac{T_1}{A_1}\frac{k}{R_3}\right)$$

For the potentiometer control circuit the source of control signal must be of low internal resistance and of constant voltage; the relevant transfer function is therefore given by eqn. (16).

The converse holds for the resistance control circuit, which is fed from a source of high internal resistance and therefore constant current, so that the transfer function is given by eqn. (18). This equation confirms the earlier analysis of the d.c. stability, since over the working range A_1 is of the order of 100 and A_3 therefore rises to very large values if R_3 only slightly exceeds kA_2, which is approximately the slope of the regulation characteristic. It confirms similarly that the time-constant T_3 is proportional to the amplification A_3 and for finite values of R_3 always exceeds T_2; T_2 in turn always exceeds T_1.

(8.6) Temperature Effects

(8.6.1) Variation of I_{c0}.

The symbol I_{c0} is generally in use to represent the collector current flowing when the emitter current is zero. It is a familiar property of transistors that it increases as an exponential function of temperature and the value measured at 0° C may be increased thirtyfold at +70° C. If this current were sufficiently large it might prevent the regulator from reducing the excitation to its level on no load. It does not appear likely that this effect will be serious in the type of transistor which has been used for the tests, since the measured value of I_{c0} at 18° C was 200 μA for the worst sample tested.

(8.6.2) Slope of Output Characteristic Curves.

It has already been shown that the slope of these curves is a critical factor in determining the d.c. stability of the regulator. The slope is equal to the output resistance of the transistor when controlled from a high-resistance source; for the common-base connection it is $(r_c + r_b)$; for the common-emitter and common-collector connections it is $r_c(1 - a) + r_e$. The collector resistance r_c decreases with temperature, but a may show an increase to an extent depending on the method of manufacture. Thus with some transistors the output resistance may fall with rising temperature and may endanger the d.c. stability unless sufficient margin of safety has been allowed. No measurements of this effect have been made.

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Nov. 1956

THE ABSOLUTE CALIBRATION OF VOLTAGE TRANSFORMERS

By W. K. CLOTHIER, B.Sc., M.E., Associate Member, and L. MEDINA, Dipl.Ing.

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SUMMARY

An account is given of equipment and measuring techniques in use at the National Standards Laboratory, Australia, for calibrating voltage transformers. The equipment employs 3-terminal air-dielectric capacitors to form a voltage divider, the ratio and phase defect angle of which are determined by a self-contained build-up technique. Owing to the use of virtually loss-free capacitors, the phase angle of the divider is negligibly small.

Two methods are described for calibrating transformers. In one, ratio balance is obtained by means of a small auxiliary variable-ratio voltage transformer, and phase balance by current injection into one of the detector bridge junctions. In the other method, ratio balance is provided by a variable 3-terminal air-capacitor in the low-voltage arm of the divider, and phase balance by voltage injection in series with that arm, a feedback amplifier providing a low-impedance injection circuit. In both methods the accuracy of measurement is approximately 2 parts in 10^5 in ratio and $0 \cdot 05'$ in phase angle.

The air-dielectric capacitors used in the voltage divider are tested to ensure that they have no significant voltage coefficient of capacitance or loss angle.

LIST OF SYMBOLS

C = Capacitance in phase-balancing circuit, farads.
C_1 = Capacitance in high-voltage arm of capacitance voltage divider, farads.
C_2 = Capacitance in low-voltage arm of capacitance voltage divider, farads.
$D = N/N_2$.
I_1 = Current in C_1, amp.
I_2 = Current in C_2, amp.
I_R = Current in R, amp.
K_a = Ratio of transformer under test.
K_n = Nominal ratio of transformer under test.
$N = N_2 - N_1$.
N_1 = Primary turns on auxiliary transformer T_2.
N_2 = Secondary turns on auxiliary transformer T_2.
R = Resistance in phase-balancing circuit, ohms.
V = Voltage on C_2, volts.
V_p = Primary voltage of transformer under test, volts.
V_s = Secondary voltage of transformer under test, volts.
α = Fraction of the voltage V on R.
ϕ = Phase angle, rad.
ω = Angular frequency, rad/sec.

(1) INTRODUCTION

During recent years measuring facilities have been set up at the National Standards Laboratory, Australia, for testing voltage transformers, principally those of high precision required for use as standards in the various government, semi-government and industrial laboratories throughout Australia. In considering possible methods for testing these transformers, the use of an absolute technique was regarded as mandatory, not only because of the Laboratory's particular responsibilities as a standardizing authority, but also because of its distance from the corresponding laboratories of other countries, which might otherwise have been called upon to provide calibrations had a relative method been adopted.

Of the various absolute methods considered, those involving a null balance in a bridge circuit were the only ones showing promise of satisfactory accuracy. In general, absolute null methods make use of some form of voltage divider for comparing the primary and secondary voltages of the transformer under test. Resistance dividers[1, 2, 3] have been used for voltages up to about 150 kV, but owing to the measures that must be taken to control unavoidable capacitances, the bulk of this type of divider, together with its shield, is very considerable, even when its rating is only a few tens of kilovolts. With available resistance alloys there seems little prospect of extending the working voltage of highly precise resistance dividers much beyond 50 kV.

As appreciably higher voltages were of immediate interest, and as facility for extension to still higher voltages was desirable, attention was turned to other forms of divider, in particular to circuits employing air or compressed-gas capacitors in the high-voltage arm. The methods due to Churcher,[4] Dannatt,[5] Yoganandam[6] and Gopalakrishna,[7] shown in Fig. 1, are of this type. In Churcher's circuit [Fig. 1(*a*)] the ratio balance control is a variable mica capacitor in parallel with a variable air capacitor and the phase control comprises a mutual inductor and resistor, either of which may be varied. The other circuits, although

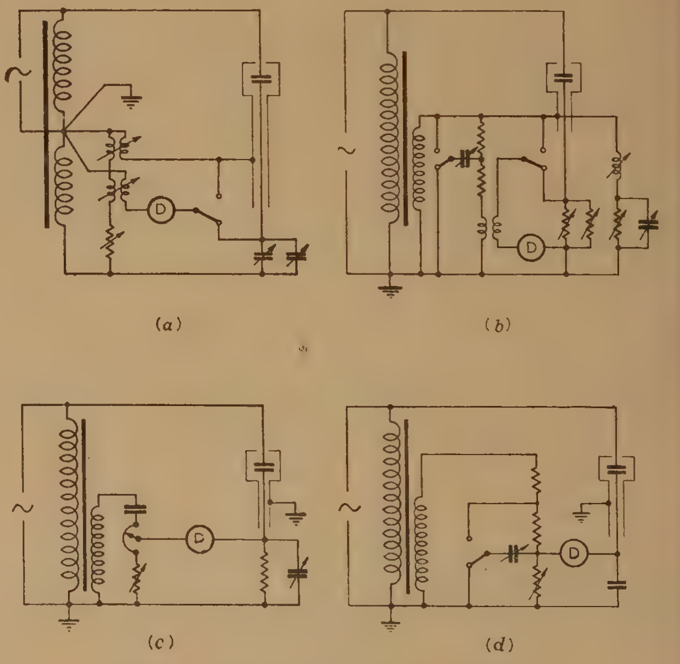

Fig. 1.—Voltage transformer testing circuits.

(*a*) Churcher's circuit.
(*b*) Dannatt's circuit.
(*c*) Yoganandam's circuit.
(*d*) Gopalakrishna's circuit.

Mr. Clothier and Mr. Medina are at the National Standards Laboratory, Commonwealth Scientific and Industrial Research Organization, Australia.

differing in principle of operation, use for the ratio control a variable resistor and for the phase control a variable mica capacitor. In addition to the balance controls, each circuit except Churcher's makes use of at least two other components—resistors, mica capacitors or mutual inductors—the values of which enter with first-order importance into the equations for ratio balance.

In two of the circuits [Figs. 1(*a*) and 1(*b*)] a subsidiary balance is required to bring the voltage of the guard to the same value as that of the detector. Yoganandam and Gopalakrishna omit the second balance, and the resulting error due to the voltage difference between the detector and the earthed guard is kept small by limiting the impedance in the lower arm of the high-voltage divider. This results, however, in reduced sensitivity in tests at low primary voltages.

(2) CHOICE OF METHOD

An attempt has been made to devise a test method suitable for all transformer ratios from 1/1 upwards, using a simple capacitance divider as in Churcher's method, but avoiding the use of mica capacitors and mutual inductors. The former require corrections, both in capacitance and in power factor, when used for precise measurements at power frequencies, and, in the case of switched mica capacitors, the corrections are apt to be different for each setting of the dials. Mutual inductors, unless fully astatic, are inconvenient as major circuit elements determining the bridge balance, owing to their susceptibility to interference from stray magnetic fields. These component limitations have been avoided in the present equipment, principally by the use of a capacitance voltage divider in which 3-terminal air-dielectric capacitors are employed in the low-voltage as well as in the high-voltage arm of the bridge. In practice this leads to considerably lower values of capacitance in the voltage divider and correspondingly higher bridge impedances, but any loss in sensitivity from this cause is offset by the use of a sensitive tuned electronic detector, and by the fact that the full secondary voltage is present in the lower arm of the divider. Later it is shown that a sensitivity better than 1 part in 10^5 has been achieved even under the least favourable conditions. Further, since the guard circuit and the detector are at earth potential, the need for a subsidiary balance does not arise.

(2.1) First Method

Two principal methods of measurement have been tested very fully. The more recent circuit, now generally used in this Laboratory, is shown in simplified form in Fig. 2. C_1 and C_2

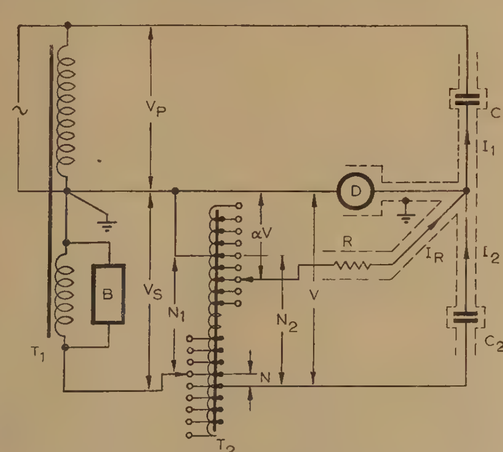

Fig. 2.—Simplified circuit of first method.

are 3-terminal loss-free capacitors forming a voltage divider whose ratio is adjusted, by choice of C_1 and C_2, to equal the nominal ratio of the transformer under test, T_1. The primary and secondary of T_1 are connected in series aiding. Errors in the ratio of T_1 are balanced by means of an auxiliary transformer T_2, whose ratio can be adjusted a little above or below unity using decade switches to control the primary turns.[8] Errors in phase angle are balanced by supplying a current I_R through a high resistance R to the junction of C_1 and C_2. I_R is in phase with the secondary voltage and therefore in quadrature with the current in C_2. Its value is adjusted by means of a switch operating on a winding on T_2. The tuned electronic detector D is connected between the earthed junction of the primary and secondary of T_1 and the junction of C_1 and C_2.

Since the detector voltage is zero at balance, the current in R is $\alpha V/R$, where αV is the voltage on R with respect to earth and V is the voltage on C_2. Since αV can have either sign, both positive and negative phase angles can be measured.

At balance $$I_1 = I_2 + I_R$$

and, since $I_1 = j\omega C_1 V_p$, $I_2 = j\omega C_2 V$ and $I_R = \alpha V/R$

therefore $$j\omega C_1 V_p = j\omega C_2 V(1 + \alpha/j\omega C_2 R)$$

or $$\frac{V_p}{V_s} = \frac{C_2}{C_1}\frac{V}{V_s}\left(1 - \frac{j\alpha}{\omega C_2 R}\right) \quad . \quad . \quad . \quad . \quad (1)$$

Assuming that the phase angle of the auxiliary transformer may be neglected and that its voltage ratio is very nearly equal to the turns ratio (see Section 2.1.4), then, if N_1 and N_2 are respectively the numbers of turns on the primary and secondary of T_2, and if $N = N_2 - N_1$,

$$\frac{V}{V_s} = \frac{N_2}{N_1} = \frac{N_2}{N_2 - N} = \frac{1}{1 - N/N_2} = \frac{1}{1 - D}$$

where D is the turns difference expressed as a fraction of the secondary turns N_2.

From eqn. (1), the phase angle is given by

$$\phi \simeq \tan\phi = \alpha/\omega C_2 R \quad . \quad . \quad . \quad . \quad . \quad (2)$$

following the sign convention for phase angle of B.S. 81: 1936.

The ratio K_a of the transformer under test is given by

$$K_a = \left|\frac{V_p}{V_s}\right| = \frac{C_2}{C_1}\frac{1}{1-D}\sqrt{\left(1 + \frac{\alpha^2}{\omega^2 C_2^2 R^2}\right)}$$

$$\simeq \frac{C_2}{C_1}\frac{1}{1-D}\sqrt{(1 + \phi^2)} \quad . \quad . \quad . \quad . \quad (3)$$

If the ratio of the capacitance divider is adjusted so that C_2/C_1 is equal to the nominal ratio K_n of the transformer, eqn. (3) becomes

$$K_a/K_n = \sqrt{(1 + \phi^2)}/(1 - D)$$

$$\simeq 1 + D + D^2 + \tfrac{1}{2}\phi^2 \quad . \quad . \quad . \quad . \quad . \quad (4)$$

the approximation being justified since D and ϕ are both small.

In the majority of cases, the simpler approximation

$$K_a/K_n = 1 + D$$

gives sufficient accuracy.

(2.1.1) Detailed Description.

The detailed circuit is shown in Fig. 3. The low-voltage capacitor comprises a number of fixed air-dielectric units, 500_b, 500_c and $1\,000_a - 1\,000_e$ (the numerals indicating the capacitances in micromicrofarads) which can be paralleled as required

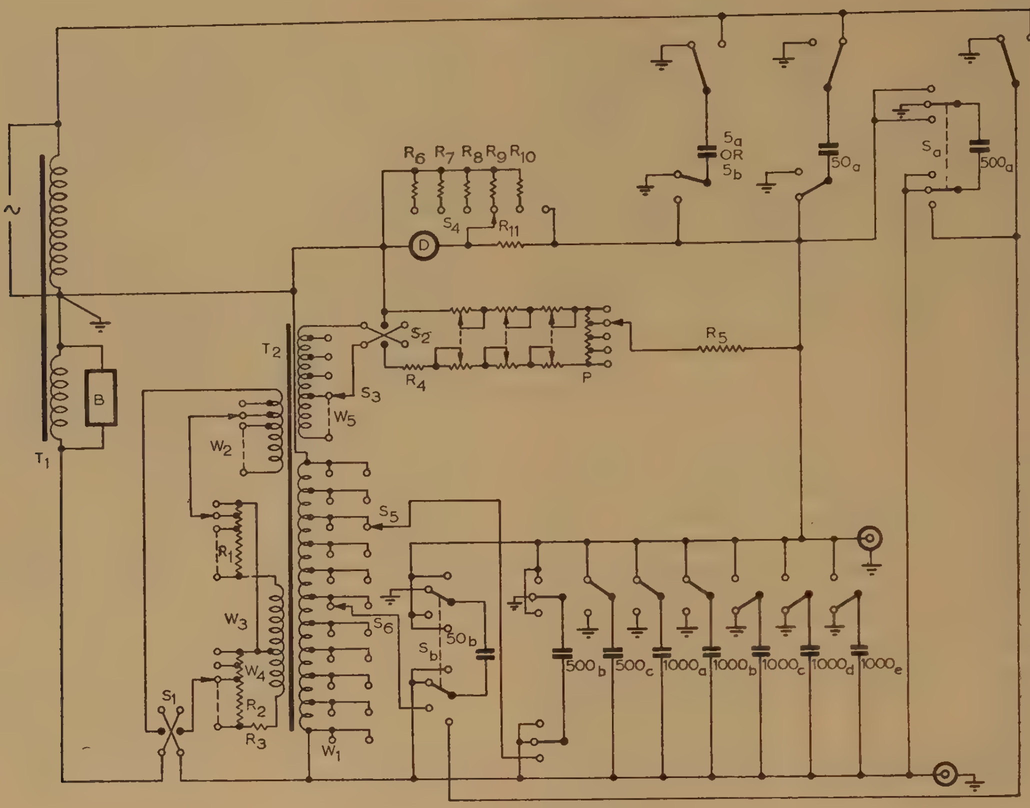

Fig. 3.—Detailed circuit diagram.

to give capacitances from 500 $\mu\mu$F to 6 000 $\mu\mu$F in steps of 500 $\mu\mu$F. The voltage rating of these units is 1·1 kV, although the voltage applied to them in normal use does not exceed 121 volts. High-voltage capacitors 500_a (1·1 kV), 50_a (11 kV), 5_a (33 kV) and 5_b (75 kV) are available for the upper arm, whilst two units, 500_a and 50_b (1·1 kV), can be connected into either arm. (A 150 kV compressed-gas capacitor is at present under construction.) All these capacitors are of 3-terminal construction with the solid insulation intercepted by the earthed guards. Since their power factors do not exceed a few parts in 10^6 the phase angle errors of the capacitance dividers may be neglected. The capacitor 50_b and those of 500 $\mu\mu$F and 1 000 $\mu\mu$F capacitance are structurally similar to the units described by one of the authors[9] except that they are not hermetically sealed. The capacitors 50_a, 5_a and 5_b are described briefly in Section 5.1. As the capacitors are required only to define a ratio, their absolute capacitance need not be known except in so far as it enters into the phase angle relationship of eqn. (2), and here it is required only to low accuracy. Hence, variations in capacitance due to changes in temperature or in moisture content and pressure of the atmosphere are of no consequence, provided that all capacitors are affected in the same degree. This is sensibly the case for all open-type units. On the other hand, a compressed-gas capacitor would be expected to show slight changes relative to the open units, but it would be unusual for this effect to exceed 1 or 2 parts in 10^4, and in any event the change would be observed and allowed for in the build-up calibration described in Section 2.1.2.

For simplicity, full details of the guarding arrangements are not shown in Fig. 3, but it should be stressed that the capacitors and the wiring to the high-impedance detector bridge point must be completely guarded. However, since each capacitor has its own earthed metal case, no large screened enclosures are necessary. The various units are interconnected by coaxial leads with the outer conductors serving as guards, and, as an additional precaution, the wiring to the low-voltage capacitors, on the side remote from the detector, is also carried out in coaxial leads in order to reduce the stray electric field in the vicinity of the more sensitive high-impedance circuits. The usual metal-braided coaxial conductor falls short of the ideal owing to the small openings between the strands of the braid. To avoid trouble from this cause, the wiring to the detector point is carried out in double-braided coaxial conductors.

By means of the switches shown in Fig. 3 the lower-arm capacitors are connected to give a capacitance ratio equal to the nominal ratio of the transformer under test, using as required a 500 $\mu\mu$F, a 50 $\mu\mu$F or a 5 $\mu\mu$F capacitor connected into the high-voltage arm. The capacitor 500_a can be transferred to this arm at the lowest position of its control switch S_a.

Additional capacitors can be connected into the lower arm for special purposes. For example, by means of a 1 250 $\mu\mu$F 3-terminal variable air-capacitor the lower-arm capacitance can be adjusted continuously throughout the range from 500 to 7 250 $\mu\mu$F. In addition, a 3-terminal micrometer capacitor is available for applications requiring fine sub-division of capacitance.

It will be noticed that the lower-arm capacitors not connected to the detector are switched to earth. This allows simple switches to be used, since all contacts of the switch are at earth potential in both positions and therefore inter-contact capacitances are of no significance. Also, a constant capacitance load is maintained in the lower arm, a result of value when the equipment is used for measurements of exceptional accuracy, as for instance in the capacitance build-up calibration described in the next Section.

The ratio balance is obtained by adjusting the number of turns in the primary circuit of the auxiliary transformer T_2. Windings

W_2 is tapped in increments of 0·1% giving a total range of 1% by means of a decade dial. Two additional decades give steps of 0·01% and 0·001% by means of low-resistance voltage dividers supplied from the windings W_3 and W_4. The dials are engraved to indicate the amount by which the quotient true-ratio/nominal-ratio differs from unity, and the sign of this difference is indicated by the position of the reversing switch S_1 controlling the connections to the winding. The auxiliary transformer is described more fully in Section 5.2.

Phase difference is balanced by means of a 5110-ohm switch-dial voltage divider P and 2-megohm resistor R_5 supplied from the secondary W_5 of the auxiliary transformer, and the sign of the phase angle is controlled by the position of the reversing switch S_2. The coarsest dial of the phase control covers a range of 40′ in steps of 10′, and three additional decade dials give steps of 1′, 0·1′ and 0·01′. The total range is thus 51·1′. For the phase angle dials to be direct reading there must be appropriate correspondence between the tapping used on the winding W_5 and the total capacitance in the lower arm, which in normal testing does not exceed 5 000 $\mu\mu$F. To provide for this, W_5 has 10 equal sections and the selector switch S_3 is set so that the number of active sections is equal to $C_2/500$, where C_2 is the total capacitance in the lower arm in micromicrofarads. W_5 has an additional winding of one-tenth the turns of the other sections, and when connection is made to this winding in the first position of S_3 the phase angle dials are direct reading when the capacitance in the lower arm is 50 $\mu\mu$F, a circuit condition that occurs during the build-up calibration.

For convenience in adjusting the detector sensitivity, an attenuator network, R_6–R_{11}, controlled by the switch S_4, is included in the measuring unit; R_{11} is short-circuited when the switch is in the position for maximum sensitivity. The impedance of the tuned amplifier can be regarded as infinite since it has no grid leak, the d.c. grid-cathode return being provided by the bridge itself through the 2-megohm phase-circuit resistor R_5. The sensitivity of the amplifier is such that 10 μV can be detected at the input. This sensitivity is ample for all conditions of use of the equipment, including the build-up calibration described in the next Section. In the course of normal transformer calibration, at rated voltage, the voltage on the detector exceeds 200 μV for 1 part in 10^5 unbalance of the bridge.

The equipment is suitable for measurements on transformers at any frequency between 20 and 60 c/s, the auxiliary transformer T_2 and the tuned detector having been designed for use over this frequency range. The phase angle dials are direct reading on 50 c/s. At any other frequency, f, their readings must be multiplied by $50/f$.

The burden on the secondary of the transformer under test, due to the decade transformer T_2 and the total lower-arm capacitance load, is approximately 0·04 VA at 110 V, 50 c/s.

(2.1.2) Capacitance Build-up.

The build-up calibration provides for the rapid intercomparison of all capacitor units so that every capacitance ratio is determined by a completely self-contained measurement. The control switches on the capacitors (Fig. 3) enable the equipment to be used both for normal testing and for the build-up calibration. The only item additional to the normal measuring equipment is a good-quality 1 100/110-volt voltage transformer which throughout the build-up takes the place usually occupied by the transformer under test.

The successive steps in the build-up will be described by reference to the functional diagrams of Fig. 4, in which the actual switching operations are represented, for simplicity, as being performed by single-pole selector switches. The switching is in fact more complicated than this (see Fig. 3) owing to the provision

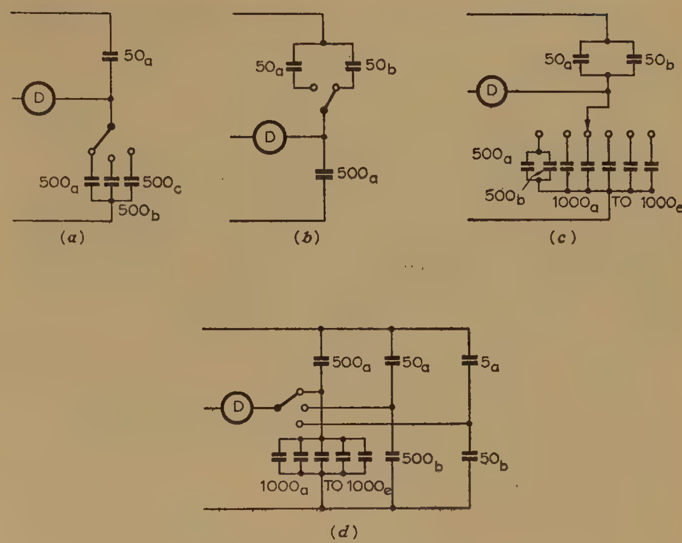

Fig. 4.—Capacitance build-up.

that must be made for earthing any capacitors that are not connected to the detector point. Fig. 4 accurately represents, however, the actual bridge-arm connections at each stage of the build-up.

Commencing with the capacitance divider arranged as in Fig. 4(*a*) and with one of the 50 $\mu\mu$F capacitors in the upper arm, the three 500 $\mu\mu$F capacitors, 500_a, 500_b and 500_c, are substituted in turn in the lower arm. From the dial readings at balance the relative capacitances and loss-angle differences of the 500 $\mu\mu$F capacitors are known. The 50 $\mu\mu$F units, 50_a and 50_b, are next intercompared as shown in Fig. 4(*b*). Capacitors 50_a and 50_b are then paralleled to give a nominal capacitance of 100 $\mu\mu$F in the upper arm as in Fig. 4(*c*), and the 1 000 $\mu\mu$F capacitors, $1\,000_a$ to $1\,000_e$, are compared with 500_a and 500_b in parallel in the lower arm.

The measurements of Figs. 4(*a*) and 4(*c*) give the relative values of all the 500 $\mu\mu$F and 1 000 $\mu\mu$F capacitors. By transferring one of the 500 $\mu\mu$F capacitors, (500_a), to the upper arm and paralleling the five 1 000 $\mu\mu$F units in the lower arm, a voltage divider of known ratio—nominally 10/1—is now formed and, as shown in Fig. 4(*d*), this is compared in turn with each of the two dividers of the same nominal ratio formed from the 50_a and 500_b capacitors and the 5_a and 50_b capacitors.

From the ratio balances obtained, the relative values of all capacitors are now known and the true value of any divider ratio formed from the capacitors can be determined with high precision. At each stage of the build-up the phase circuit switch S_3, Fig. 3, is positioned in accordance with the nominal capacitance in the lower arm, and the phase balance readings then remain unchanged throughout the build-up. Any change of significant magnitude would be evidence of anomalous power loss in one of the capacitors.

It has been found convenient to trim all capacitors by means of small external fixed trimmers so that their actual ratios are very close to nominal. The build-up procedure then becomes simply a check, and no readings need be taken nor corrections applied, provided that the balance does not change significantly at any step.

Since the capacitance build-up is basic to any subsequent measurements carried out with the equipment, adequate sensitivity must be available at each stage. The most exacting conditions occur during the substitution of the 50/5 $\mu\mu$F ratio, when the bridge impedance is a maximum. Under these conditions the

voltage change at the detector for 1 part in 10^5 capacitance unbalance is approximately 25 μV. This, however, is very easily detected using modern tuned amplifiers,[10, 11, 12, 13] and at least one has been described that is capable of detecting 1 μV under the same conditions.[12] For all other steps of the build-up the sensitivity available is 10 or more times greater.

The high sensitivity has been found useful in maintaining a closer check on the stability of the capacitors than is required merely for transformer testing, but if the equipment is to be used specifically for a purpose such as this, the 1 100/110-volt transformer must have exceptional stability. It has been found best in applications such as these to use a transformer excited from a separate primary winding, the 1 100/110 ratio being supplied by closely coupled secondary windings. In this way the ratio error and phase difference of the secondaries with respect to one another can be reduced to a few parts in 10^5 or less and the stability is improved to a corresponding degree.

(2.1.3) Stability of Capacitors

During the period of approximately five years since the capacitors were first put into service, the relative values of the various 500 $\mu\mu$F and 1 000 $\mu\mu$F units have remained unchanged within 1 part in 10^5 at all times. Similar stability has been observed for the 50 $\mu\mu$F and 5 $\mu\mu$F capacitors under normal laboratory conditions, but under exceptional conditions—rapidly changing temperature or relative humidity—temporary changes up to 3 parts in 10^5 have occurred in ratios involving the use of these units. Since the complete build-up calibration can be carried out in quite a short time—less than 10 min—a check for any change in ratio is very easily made.

(2.1.4) Errors in the Measuring Circuit.

Owing to various small errors arising in the measuring circuit, the actual ratio and phase angle of a transformer may differ slightly from the values computed from eqns. (2) and (3). In Tables 1 and 2 the various sources of error for 50 c/s operation

Table 1

RATIO ERROR

Cause of error	Dial settings for maximum error	Maximum error
Ratio error of auxiliary transformer	All ratio dials set at 10	10×10^{-6}
Phase error of auxiliary transformer	Setting 50′	$\sim 2 \times 10^{-6}$
Reactance of R	Setting 50′	$< 5 \times 10^{-6}$

Table 2

PHASE ANGLE ERROR

Cause of error	Dial settings for maximum error	Maximum error
Phase error of auxiliary transformer	All ratio dials set at 10	$\sim 0{\cdot}015'$
Ratio error of auxiliary transformer	Setting 50′	$\sim 0{\cdot}006'$
Change in resistance of phase-balance circuit with dial setting	Approx. 25′	$\sim 0{\cdot}035'$

are given; also the conditions under which the error is a maximum and the magnitude of this maximum. Errors due to inaccuracy of adjustment of the resistors in the phase-angle and ratio circuits are not included in the Table since they are negligibly small. It is seen that under the least favourable conditions the total errors arising in the measuring circuit do not exceed 2 parts in 10^5 in ratio and $0{\cdot}05'$ in phase angle.

The error in ratio of 5×10^{-6} given in Table 1 as due to the reactance of R is based on an assumed time-constant of 10^{-6} sec for the resistor, which is wire wound and has a value of 2 megohms. A time-constant lower than this is easy to achieve, either by the form of the winding or by the use of compensation, but the wiring of the resistor into the bridge must be carried out carefully to avoid additional stray capacitance in shunt with the resistor. The judicious use of a shield is helpful in this connection.

(2.1.5) Non-Standard Ratios.

The equipment as described above provides for the calibration of transformers with nominal ratios of 1/1, 2/1, 3/1, 4/1, 5/1, 6/1, 7/1, 8/1, 9/1, 10/1, 11/1, 12/1, also 10-fold and 100-fold multiples of these ratios. In tests at intermediate ratios the effective capacitance of one or more of the fixed units is varied in steps of 10% of its maximum value by connecting it to tappings on the winding W_1 of the auxiliary transformer T_2 in Fig. 3. In this way one of the 500 $\mu\mu$F units (500_b), using the switch S_5, provides capacitances from 50 $\mu\mu$F to 500 $\mu\mu$F in steps of 50 $\mu\mu$F, and a 50 $\mu\mu$F unit (50_b), using the switch S_6, gives values from 5 $\mu\mu$F to 50 $\mu\mu$F in steps of 5 $\mu\mu$F. By means of these two capacitors, together with the other fixed units, effective lower-arm capacitances from 500 $\mu\mu$F to 6 050 $\mu\mu$F can be selected in steps of 5 $\mu\mu$F. This degree of sub-division is sufficient to allow a bridge balance to be obtained for any ratio by means of the ratio controls of the measuring circuit. The accuracy depends upon the precision of sub-division of voltage in the tapped winding W_1. Taking into account the errors of this transformer, and bearing in mind that the contribution to the total effective lower-arm capacitance by the capacitors connected to the tappings on W_1 never exceeds 50%, it is found that the errors do not exceed 2×10^{-5} in ratio and $0{\cdot}1'$ in phase angle.

An alternative method for testing transformers with non-standard ratios makes use of a 3-terminal variable air capacitor in the lower arm to provide a capacitance ratio equal to the nominal ratio of the transformer under test.

(2.2) Second Method

The second principal method of testing voltage transformers that has been investigated in detail is shown in Fig. 5. The

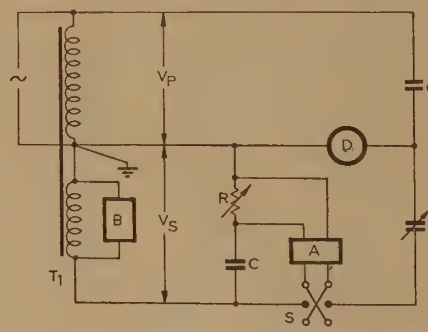

Fig. 5.—Simplified circuit of second method.

capacitance divider is identical with that previously described except that one of the 1 000 $\mu\mu$F fixed capacitors is replaced by a 1 250 $\mu\mu$F 3-terminal variable air capacitor, thus enabling the capacitance in the lower arm to be adjusted continuously throughout the range from 500 $\mu\mu$F to 6 250 $\mu\mu$F. Ratio balance is obtained by varying this capacitor, finer sub-division being provided, when necessary, by means of a micrometer capacitor connected in parallel.

Phase balance is obtained by injecting a quadrature correcting-voltage in series with the lower arm. This voltage is derived from a variable resistor R and capacitor C shunted across the secondary of the transformer under test, T_1. The voltage on R is applied to the input of a feedback amplifier, A, with a gain of unity, and the output appears in a winding of an output transformer in the feedback loop. Reversal of the phase of the injected voltage is carried out by reversing the connections to this winding.

The voltage on the phase-balancing resistor R is

$$j\omega CRV_s/1 + j\omega CR$$

Since A has a gain of unity, the voltage on C_2 at balance is $V_s \pm j\omega CRV_s/1 + j\omega CR$, the sign depending upon the position of the reversing switch, S, in the output circuit of the amplifier.

The current in C_2, therefore, is

$$j\omega C_2V_s(1 \pm j\omega CR/1 + j\omega CR) = j\omega C_1V_p$$

since the currents in C_1 and C_2 are the same at balance.

Hence

$$V_p/V_s = \frac{C_2}{C_1}\left(1 \pm \frac{j\omega CR}{1 + j\omega CR}\right)$$

$$= \frac{C_2}{C_1}\left(1 \pm \frac{\omega^2C^2R^2 + j\omega CR}{1 + \omega^2C^2R^2}\right)$$

$$= \frac{C_2}{C_1}\left(\frac{1 + 2\omega^2C^2R^2 + j\omega CR}{1 + \omega^2C^2R^2}\right) \text{ or } \frac{C_2}{C_1}\left(\frac{1 - j\omega CR}{1 + \omega^2C^2R^2}\right) \quad (5)$$

From eqn. (5), the phase angle ϕ of the transformer is given by

$$\tan\phi = -\frac{\omega CR}{1 + 2\omega^2C^2R^2}, \text{ or } \omega CR \quad . \quad . \quad . \quad (6)$$

respectively, for negative and positive phase angles in accordance with the sign convention of B.S. 81: 1936.

For most purposes the term $2\omega^2C^2R^2$ is negligible and it is sufficient to use the approximation

$$\phi \simeq \tan\phi \simeq \mp\,\omega CR \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Neglecting 4th and higher powers of ωCR, eqn. (5) gives for the ratio K_a

$$K_a = \left|\frac{V_p}{V_s}\right| = \frac{C_2}{C_1}(1 + \tfrac{3}{2}\omega^2C^2R^2) \text{ or } \frac{C_2}{C_1}(1 - \tfrac{1}{2}\omega^2C^2R^2)$$

$$\simeq \frac{C_2}{C_1}(1 + \tfrac{3}{2}\phi^2) \text{ or } \frac{C_2}{C_1}(1 - \tfrac{1}{2}\phi^2) \quad . \quad (8)$$

In the majority of cases the terms in ϕ^2 can be neglected so that

$$K_a \simeq \frac{C_2}{C_1}$$

In practice there are small departures from the relationships of eqns. (7) and (8) due chiefly to the phase-defect angle of C and the finite output impedance of the amplifier. The former gives a ratio error proportional to the product of the phase-defect angle and the indicated transformer phase angle. With a mica capacitor of reasonable quality for C, the defect angle is less than 10^{-3} rad and the error in ratio is then less than 10^{-5} at an indicated phase angle of 35′. The error due to capacitance current flowing in the output impedance—approximately 10 ohms resistance—of the amplifier is almost constant at 0·07′ for 50 c/s operation. No significant error occurs owing to incorrect amplifier gain since it differs from unity by less than 0·1%.

The capacitance build-up calibration is carried out by a procedure generally similar to that described in Section 2.1.2 for the first method.

(2.3) Comparison of the Methods

Both methods of testing described above are capable of high accuracy, and in this respect there is little to choose between them. Experience with the fixed capacitors, however, showed their stability to be considerably superior to that of the best available variable air capacitors, and the advantages of this high stability could be more fully realized in the first method. At the same time, the use of decade switches for the ratio dials and the elimination of any form of valve amplifier from the main bridge network were considered to be points in favour of this method. For these reasons the first method was adopted for general testing work.

It is worth noting that alternative combinations of the techniques described for ratio and phase measurement have certain advantages, in particular one employing the ratio control of the first method and the phase control of the second, but a discussion of these alternatives is beyond the scope of the paper.

(2.4) Auxiliary Tests

A number of useful check tests have been employed at various stages in the development of the equipment, and some have been adopted as routine because of their value in periodical checking.

(2.4.1) Tests for Variation of Capacitance with Voltage.

One of the more important tests is that used to confirm that the capacitances are independent of the applied voltage up to their maximum working limits. It was pointed out earlier that, in the build-up calibration, the maximum voltage on the 50 $\mu\mu$F and 5 $\mu\mu$F capacitors is 1 100 volts, whereas the working voltages on these units during transformer testing are very much higher—11 kV (nominal) for the 50 $\mu\mu$F unit; 33 kV and 75 kV for the 5 $\mu\mu$F units.

The 11 kV and 33 kV capacitors were tested in the following way. Using a voltage transformer to provide ratio arms in the circuit of Fig. 3, the bridge was first balanced using a capacitance divider with the test capacitor in the upper arm. This divider was then replaced by another of the same nominal ratio, but with a higher-rating capacitor in the upper arm, and the bridge was rebalanced. By repeating the substitution at various voltages up to the limiting working voltage of the test capacitor, any alteration in its capacitance or power factor could be detected. In this way, for example, the 11 kV 50 $\mu\mu$F capacitor, with 5 000 $\mu\mu$F in the lower arm, is tested by comparison with the 33 kV 5 $\mu\mu$F capacitor, with 500 $\mu\mu$F in the lower arm, up to the maximum working voltage of 11 kV + 10% applicable to the 50 $\mu\mu$F unit. The 33 kV 5 $\mu\mu$F capacitor, with a suitable value of capacitance in the lower arm, is then compared with the 75 kV 5 $\mu\mu$F capacitor using any convenient voltage transformer capable of supplying 33 kV + 10%.

There remains the 75 kV 5 $\mu\mu$F capacitor to be checked at voltages above 33 kV + 10%. In the absence of other 3-terminal capacitors to cover this range, recourse must be had to indirect methods of test, and two such methods have been used. Both are based upon the observation that, in 3-terminal capacitors of sound design, any capacitance change or increase in power loss with increase in the applied voltage is invariably associated with corona discharge which appears abruptly at a particular voltage and then increases rapidly with rising voltage. In one method the assumption is made that, when testing a good-quality transformer by means of the capacitor under examination, the absence of any anomalous change in the measured ratio or phase angle with increasing voltage is evidence of satisfactory capacitance

behaviour. The second test has been described by one of the authors[14] and is found to be very reliable, for both high- and low-voltage capacitors. In this test, discharges are detected under normal a.c. conditions by observing the existence of a d.c. component in the current to the guarded electrode. Such a direct current has invariably been found associated with discharges in air-dielectric capacitors, and, unlike r.f. detection methods, the d.c. technique discriminates between discharges to the guard and to the working electrode.

The tests described above have given complete agreement when used for determining the safe working limits of voltage on the capacitors for measuring purposes.

(2.4.2) Check Tests using a Calibrated Transformer.

Having carried out the build-up calibration and the checks for voltage independence, the capacitors can, if desired, be used to calibrate one or more transformers, and then, reversing the order, subsequent tests on the transformers can serve as a check on the capacitors, at least within the limits of stability of the transformers. This procedure has been adopted as routine in the Laboratory, and before testing a voltage transformer a check test on the same nominal ratio and at the maximum working voltage is carried out on a suitable laboratory voltage transformer reserved for the purpose. Experience has shown that the measured ratio and phase angle of the check transformers remain constant to better than 1 part in 10^5 under laboratory conditions with controlled air temperature.

(2.4.3) Check on the Capacitance Build-up.

The Laboratory has available a high-quality 6·6 kV 150 000-ohm resistance divider, constructed for another purpose, and this has been used to check the capacitance build-up at reduced voltages. At voltages up to half the nominal rating of the divider the actual divider ratios agree with the nominal within 1 part in 10^5, and, by suitable interconnections, all the standard ratios and a large number of non-standard ratios are available. The capacitance ratios were checked using the transformer ratio bridge shown in Fig. 6. With the detector switched to the

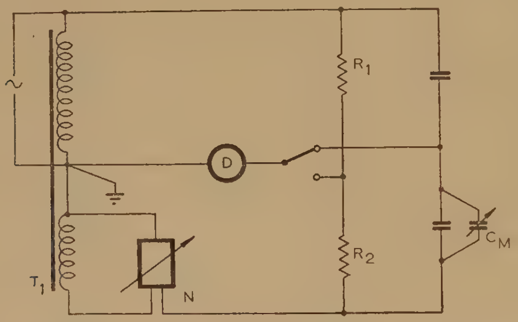

Fig. 6.—Check of capacitance ratio against resistance divider.

resistance divider, the bridge was first balanced by adjusting the magnitude and phase controls of a low-impedance correcting network, N, on the secondary of a voltage transformer, T_1, of nominal ratio equal to the resistance ratio. The detector was then transferred to the capacitance divider and the latter was adjusted to the same ratio by means of the micrometer capacitor C_M, any necessary phase adjustment again being taken up by means of the phase control. In this way the capacitance ratio was adjusted for equality with the resistance ratio. The capacitance ratio obtained by means of the resistance divider agreed with that given by the capacitance build-up within the limits of accuracy of the measurements, i.e. approximately 1 part in 10^5.

The resistance divider does not provide a useful check on the power factor of the capacitors, since the phase angle of the divider is relatively large and varies with the ratio. Because of its excellent stability, this divider has at times been used as a reference standard for setting the ratio of the capacitance divider when testing transformers with non-standard ratios.*

(2.4.4) Influence of Primary and Secondary Interconnections.

In the methods of calibration described above, the transformer primaries and secondaries are connected in series aiding. To check for a possible effect of dielectric admittance currents on the ratio or phase angle, depending upon the interconnection used, a carefully balanced 110/110-volt isolating transformer was connected in cascade with the secondary of the transformer under test and the ratio and phase angle of the combination were measured for the series-aiding and series-opposing connections of the test transformer secondary. No significant difference has been observed in many tests carried out in this way.

On the other hand, appreciable changes have been observed when the primaries of high-voltage transformers are reversed. For example, out of eight 33 kV transformers with fully insulated primaries, seven showed measurable changes, the greatest however being only 1·7 parts in 10^4 in ratio and 0·09′ in phase angle, and this result was obtained in a test at a frequency of 50 c/s on a transformer rated at 25 c/s. In every case the reversal effect was very small, so much so that in order to measure the effect it was essential to maintain a close control on voltage and frequency.

(3) CONCLUSIONS

Two absolute methods have been developed for the precise measurement of the errors of voltage transformers. The standard of ratio employed is a capacitance voltage divider of negligible phase angle formed from 3-terminal air-dielectric capacitors, the relative values of which are determined by a build-up calibration. The sensitivity and accuracy are such that ratio can be measured to 2 parts in 10^5 and phase angle to an equivalent accuracy.

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* The authors' attention has been drawn to a paper on the absolute calibration of voltage transformers (*VDE-Fachberichte*, 1953, 17) by H. E. Linckh, who describes a detailed technique for calibrating a capacitance divider by comparison with a resistance divider of known ratio and phase angle.

(9) Clothier, W. K.: 'A Fixed Gas-Dielectric Capacitor of High Stability', *Proceedings I.E.E.*, Paper No. 1679 M, August, 1954 (**101**, Part II, p. 453).
(10) Rayner, G. H.: 'A Selective Detector Amplifier for 10–10 000 c/s', *Journal of Scientific Instruments*, 1953, **30**, p. 17.
(11) Looms, J. S. T.: 'A Null-Detector for Power Frequency Bridges', *ibid.*, 1953, **30**, p. 290.
(12) Clothier, W. K., and Smith, W. E.: 'A Tuned Detector-Amplifier for Power Frequency Measurements', *ibid.*, 1955, **32**, p. 67.
(13) Clothier, W. K., and Hawes, F. C.: 'A Tuned Differential Amplifier for Low Frequency Bridges', *Australian Journal of Applied Science*, 1956, **7**, p. 38.
(14) Medina, L.: 'The Detection of Corona Discharges in High Voltage Air Capacitors', *ibid.*, 1955, **6**, p. 453.

(5) APPENDICES

(5.1) High-Voltage Capacitors

The electrode arrangements and the approximate proportions of the 11 kV, 33 kV and 75 kV capacitors are shown in Fig. 7. Leading dimensions are given on the diagrams. All capacitors are of 3-terminal construction, and in each case the location of the solid insulating material is such that it has no appreciable influence on the direct capacitance or power factor.

The 11 kV 50 $\mu\mu$F unit [Fig. 7(*a*)] is a parallel-plate capacitor with the two assemblies of crossed rectangular plates supported on ceramic insulators from a heavy metal base. The electrodes of the 33 kV 5 $\mu\mu$F unit [Fig. 7(*b*)] are concentric cylinders, closed at the upper ends, the outer cylinder serving as the high-voltage electrode. The 75 kV 5 $\mu\mu$F, Petersen-type capacitor [Fig. 7(*c*)] has been constructed to satisfy a temporary need until a compressed-gas capacitor becomes available. Although of very simple construction it has given completely satisfactory performance. The inner cylindrical low-voltage electrode and guard electrodes are made from brass tubing, and the outer cylinder from rolled brass sheet.

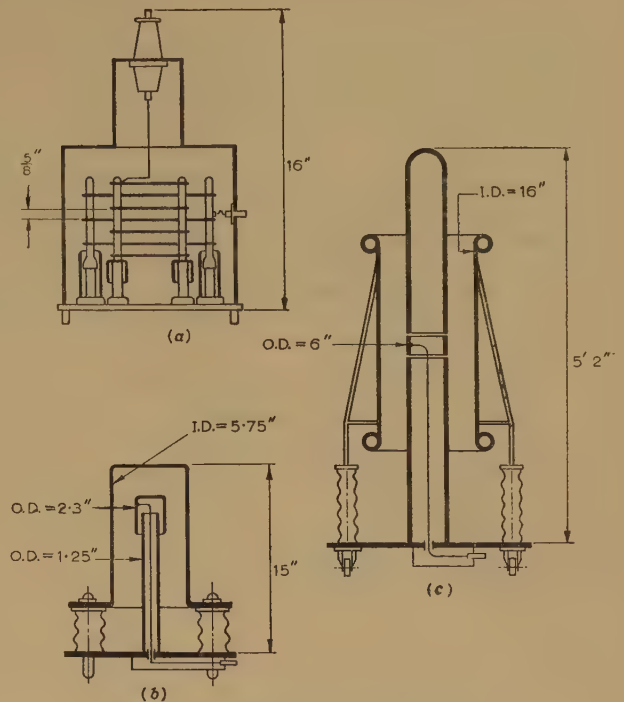

Fig. 7.—High-voltage capacitors.
(*a*) 50 $\mu\mu$F 11 kV capacitor.
(*b*) 5 $\mu\mu$F 33 kV capacitor.
(*c*) 5 $\mu\mu$F 75 kV capacitor.

(5.2) The Auxiliary Transformer

The auxiliary transformer (T_2 in Fig. 3) has a $2\frac{1}{8}$ in core of Telcon type 113N 0·015 in Mumetal laminations, singly interleaved. Details of the windings are given in Table 3, the notation being the same as in Fig. 3. The winding order is the order of entry in the Table, W_2 being the innermost winding. The ten sections of W_1 are connected in a sequence giving minimum errors in sub-division of voltage. Denoting the ten sections by 1 to 10, the sequence of connections is 6–5–7–4–8–3–9–2–10–1. The primary current of T_2 at 110 volts is 0·25 mA at 50 c/s and 0·5 mA at 20 c/s. These figures are for the transformer loaded with the resistors R_1, R_2 and R_3 and with the voltage divider P bridging the whole of winding W_5. The influence of the capacitance load due to the low-voltage capacitors and guard circuits is to modify the primary current at 110 volts to 0·35 mA at 50 c/s and 0·45 mA at 20 c/s.

Table 3

Winding	Number of turns	Taps at	Wire
W_2	30	Every 3 turns	16 B. & S. S.S.E.
W_3 and W_4 ..	4	3 turns	0·005 in shim copper 2 in wide
Electrostatic shield	1	—	0·002 in shim brass
W_1	10 × 300	—	29 B. & S. S.S.E.
Electrostatic shield	1	—	0·002 in shim brass
W_5	150	$1\frac{1}{2}$ turns and every 15 turns	23 B. & S. S.S.E.

DISCUSSION BEFORE THE MEASUREMENT AND CONTROL SECTION, 4TH DECEMBER, 1956

Mr. D. Edmundson: Nothing is easier than to design a bridge circuit, but nothing is more difficult than to design a good one. The first of the two described in the paper is singularly free from almost any kind of objection.

A bridge circuit is judged not only—or even primarily—on its accuracy but also on such matters as the following. Is it direct-reading? Does the screen require a separate balance? Are the two adjustments independent? Can a spurious balance be obtained? The authors' circuit is satisfactory on all these counts. Its most important innovation is the use of a gas-dielectric condenser at the l.v. end of the divider, made possible by developments in amplifier-galvanometers. The objection to the mica condenser universally used is not that its phase angle, differing from zero, introduces inaccuracies: such an error, which need be only of the order of 0·1% or less, say 1–3 min, can be accurately known and allowed for. It is that, since a correction has to be made, the bridge is not direct-reading. Again, the introduction of the auxiliary transformer, made possible by the development of high-permeability alloys, makes direct reading possible in all normal circumstances. The authors disarm criticism by referring to its negligible burden, but more detail of its design would be appreciated.

In the second circuit, which is only briefly referred to, the authors give no details of the amplifier. I do not doubt that it can be made, but, in work of this sort, the point has hardly been reached where an amplifier—which, after all, is an essential

part of the circuit—can be represented by a rectangle without reference to its design.

How far use can be made of the accuracy now achieved by the authors is perhaps a philosophical question. Occasionally, a voltage transformer has to be calibrated in a laboratory for use as a secondary standard, but the calibration accuracy would depend on its stability. Or, for a special measurement, e.g. that of the heat-rate of a turbine, extremely accurate integrators may justify a corresponding accuracy in associated equipment. Again, in measuring the short-circuit loss of a large power transformer, the circuit phase-angle of perhaps 3° or 4° requires a very low phase-angle error in the instrument transformers. Most voltage transformers are, however, designed to supply relays or meters of commercial accuracy, and it is doubtful if present methods of calibration have ever introduced significant errors. It is on the other grounds which I have mentioned that I hope to see the authors' circuit introduced into this country as general practice in the transformer industry.

Mr. H. D. Hawkes: I think it would be advisable to call the authors' method of calibration a 'direct method' as opposed to the 'difference methods' using a standard transformer for reference. In both these methods, where the out-of-balance signal has to be resolved into active and reactive components, high accuracy is approached only where the error signal is relatively small.

The authors claim an accuracy of 2 parts in 10 for both[5] ratio and phase angle for their method, which is dependent on both frequency and waveshape. I should like to ask if this is realistic in view of the h.t. supply required.

I should like to see the national laboratories develop a direct method of measurement which would give errors of voltage transformer under practical conditions of, say, 1% or 2% harmonic distortion in the supply voltage. This method would, of course, be complex and could only be undertaken by a national concern, but it could produce some valuable information. It would mean using a device other than a fundamental detector, which covers a multitude of sins.

Table 1 of the paper gives the cumulative errors due to an auxiliary transformer. It would be interesting to know the actual errors of this transformer and how they were measured. In Section 2.4.1, in contradiction to the title of the paper, the use of an absolute transformer for checking a calibration method is mentioned, and the authors make a somewhat hazardous assumption in respect of a voltage transformer on increasing voltage. A 50% increase or decrease in voltage on a good transformer (class A) can give a change in error in ratio of 1 part in 10^4 and a phase-error change of 1·5 min.

Mr. A. Felton: The methods of calibration described have achieved an accuracy far beyond anything that has been obtained before on voltage transformers, and there is no doubt that the paper will become a classic on the subject. Further, by careful attention to every detail, the authors have anticipated every reasonable criticism.

One of the very few technical objections to the method is that the transformer is not tested under the conditions of use. In the first place, the primary and secondary are connected in series aiding, and although no differences due to dielectric admittances have yet been found, it cannot be assumed that all transformers will be equally good in this respect. Secondly, one side of the primary is earthed, whereas in some 3-phase transformers both terminals are, in normal use, at a high potential to earth. It must, of course, be admitted that this defect is shared by all the well-known voltage-transformer testing circuits, and hitherto, with the limited accuracy that has been obtainable, any differences between conditions of use and conditions of test have been considered to be negligible. But with the greatly improved accuracy achieved by these new circuits the differences may be significant, and if the authors are considering any further work they might direct some attention to this aspect of the subject.

Mr. J. K. Webb: For use at the high voltages which the authors consider, instrument transformers must be quite large and expensive. It would enhance the value of the paper if the illustrations of the high-voltage capacitors shown in Fig. 7 were supplemented by similar illustrations of the transformers. An economical procedure is to provide a tertiary winding on a mains transformer so that it can be used both to supply power and to serve as a means of measuring the output voltage. This method became popular in the cable industry about 1930, when a modified Schering bridge was used to measure voltage which was given directly in terms of the tertiary voltage and the bridge settings at balance. The circuit was similar to that of Yoganandam shown in Fig. 1(*c*), and an accuracy of 1 part in 1 000 was claimed. Would the authors, in the light of their investigation, agree with this figure, or do they think that there is anything much to be gained from their rather more elaborate circuit, bearing in mind the deficiencies involved in using a mains transformer as an instrument transformer?

Mr. G. W. Bowdler: I have recently measured the errors of voltage transformers with the aid of *ad hoc* equipment, using the circuit of the authors' Fig. 1(*a*). The procedure is equally applicable to any circuit in which a small fraction of the primary voltage is balanced against a fraction of the secondary. Ample sensitivity is obtained if these fractions are of the order of 1 volt.

Before the transformer test, the voltage dividers which it is proposed to use are connected together (Fig. A) to form a

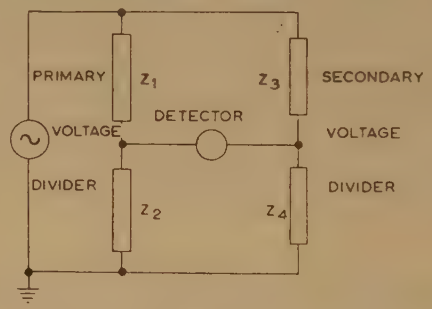

Fig. A

simple bridge which may conveniently be fed from the transformer secondary winding and balanced by adjustment of Z_2 or Z_3. The voltage across Z_2 and Z_4 under these circumstances will be only about $1/k$ volt, where k is the transformer ratio. Nevertheless, with a high-impedance detector sensitive to 1 μV, the bridge can still be balanced correct to 1 part in 10^4 for values of k up to 100. For transformers with higher ratios it may be necessary to operate the bridge at correspondingly higher voltages.

At balance,
$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4} \qquad \text{(A)}$$

The transformer is then tested by connecting the dividers across their respective windings and balancing the bridge by alteration of Z_4 to a value Z_4' ($\simeq kZ_4$), keeping Z_1, Z_2 and Z_3 unchanged.

At balance,
$$\frac{V_p}{V_s} = \frac{Z_1 + Z_2}{Z_2}\,\frac{Z_4'}{Z_3 + Z_4'} \qquad \text{(B)}$$

Eqns. (A) and (B) give
$$\frac{V_p}{V_s} = \frac{Z_4'}{Z_4}\,\frac{Z_3 + Z_4}{Z_3 + Z_4'} \qquad \text{(C)}$$

Since Z_3 is large compared with Z_4 and Z'_4, the second fraction of eqn. (C) is nearly unity and the transformer ratio and phase angle are determined almost entirely by the relative magnitudes and phase angles of Z_4 and Z'_4.*

In tests on a 66 000/110 volt transformer, the divider on the primary side might consist of a 50 pF standard high-voltage capacitor in series with a 2 μF mica capacitor, giving a nominal divider ratio of 40 000 : 1. With a resistive secondary divider, a standard 4-terminal 1-ohm shunt of short time-constant would be used for Z_4 in the preliminary balance, which would be effected by adjustment of the magnitude (approximately 40 kilohms) and phase angle of Z_3. This value of Z_3 would impose a negligible burden on the transformer in the subsequent test, in which balance would be obtained by adjustment of the magnitude (approximately 600 ohms) and phase angle of Z'_4.

It is not difficult to ensure that the impedances Z_1, Z_2 and Z_3 remain constant throughout the tests, and this is the only demand made on them; their actual values are immaterial and a tedious intercomparison of these values is therefore unnecessary.

In conclusion I should like to ask the authors whether they have experienced any difficulty in obtaining a good balance when their detector is switched to full sensitivity. There must be a small unbalance of harmonic components of the voltage wave which, in spite of the sharply tuned detector, might prevent the attainment of a null reading.

* If a potentiometer type of divider were used on the secondary winding, the second fraction of eqn. (C) would be exactly unity, and a direct reading of ratio could be obtained.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. W. K. Clothier and **L. Medina** (*in reply*): Both Mr. Edmundson and Mr. Hawkes raise, with some justification, the question as to what use can be made of the high accuracy of our method of measurement. This may to many be a philosophical question, but we feel that to the national laboratories, charged with the maintenance of standards of measurement, it is a matter of very practical importance. In the experience of most standardizing laboratories the work of calibration is more reliable and more economical of time and effort when a factor of perhaps 5 or 10 in accuracy is in hand, over and above the accuracy demanded by virtue of the quality and performance of the instrument under test. In our equipment we have done little better than to achieve this objective for the important class of high-quality transformers used as reference standards. At the same time we have had in mind other important applications of the equipment, e.g. the calibration of transformer testing sets. Where somewhat lower accuracy is sufficient, a simpler circuit arrangement is possible in which only one capacitor is used in the lower arm, its effective value being adjusted in steps by means of tappings on the secondary of the auxiliary transformer, in the manner described in Section 2.1.5.

The following additional information is given with reference to the auxiliary transformer and the associated resistance dividers. R_1 is in 10 sections each of 0·2 ohm, R_2 is in 10 sections each of 0·1 ohm, R_3 and R_4 are 2·33 and 360 ohms, respectively. At 50 c/s the maximum ratio error of this transformer with W_1 as primary and $W_2 + W_3 + W_4$ as secondary is 0·1%, and under the same conditions the ratio error between W_1 and W_5 is 0·11%. The corresponding phase differences are about 0·5′. These errors were measured in a circuit similar to that of Fig. 5, using the auxiliary transformer in the place of the transformer under test, T_1.

The amplifier A in Fig. 5 was designed some years ago, and with the modern valves and electronic techniques now at one's disposal alternative circuits would be preferred. However, the amplifier has given reliable service, and the circuit, shown in Fig. B, is of

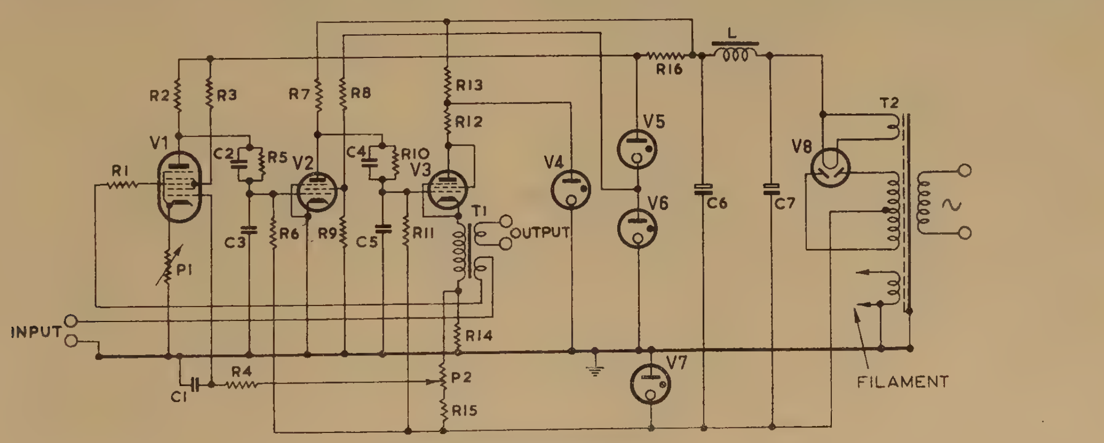

Fig. B—Feedback amplifier.

R1, R12	5 kΩ	C1	4 μF
R2	220 kΩ	C2	0·000 5 μF
R3	60 kΩ	C3	0·004 μF
R4, R5, R10	0·5 MΩ	C4	0·000 1 μF
R6	1·5 MΩ	C5	0·005 μF
R7	0·4 MΩ	C6, C7	16 μF
R8	25 kΩ	V1	6SA7
R9	7 kΩ	V2	6SJ7
R11, R15	1 MΩ	V3	6AC7
R13	9 kΩ	V4, V6, V7	VR150
R14	250 Ω	V5	VR75
R16	4·7 kΩ	V8	5Y3G

T1: 126 pairs of Telcon type 24T Mumetal laminations butt-jointed. Primary, 1 800 turns 34 s.w.g. SSE wire; each secondary, 360 turns 26 s.w.g. SSE wire. Primary inductance with 8 mA d.c., 35 H.

T2: 240/2 × 385 V, 6 V, 5 V.
L 20 H.
P1 1 kΩ, P2 15 kΩ } Preset adjustment.

interest. The three amplifier stages are directly coupled, using positive and negative stabilized voltage sources in order to keep the grid potentials near earth potential. For stabilizing the d.c. levels a d.c. feedback path is provided from the cathode of the last stage to the No. 1 grid of the 6SA7 pentagrid valve, and a low-pass filter prevents a.c. feedback via this path. It should be noted that the transconductance of the No. 1 grid of the 6SA7 is negative with respect to its anode, thus giving correct phasing of the feedback circuit. The output is taken from the secondary of a 5/1 step-down transformer, the primary of which is in the cathode circuit of the last stage. A.C. feedback is provided by another secondary of equal turns symmetrically disposed with respect to the primary and connected between the input terminal and the No. 3 grid of the input valve. The problem of achieving stability at low frequencies is eased, since the filter in the d.c. feedback path is a single-section *RC* network terminated by the grid impedance of a valve. High-frequency stability is assisted by the use of small capacitors in the grid circuits of the second and final stages. The amplifier output impedance of 10 ohms is almost entirely due to the d.c. resistance of the output winding.

In reply to Mr. Hawkes, our experience is that the ratio of a normal good-quality transformer determined with reference to the fundamental components of primary and secondary voltage is not influenced significantly by 2% of harmonic in the supply voltage. On the other hand, there may be some influence on the ratio of the r.m.s. voltages, the most serious effect arising from the simultaneous presence of harmonics in the supply together with harmonic generation of the same frequency within the transformer. It can be shown that the fractional effect on the r.m.s. ratio due to this may have a maximum value, depending on phase considerations, equal to the product of the two harmonic components. For example, with 2% of third-harmonic in the supply and a typical value of 0·25% generated third-harmonic voltage, the maximum difference between the r.m.s. ratio and the fundamental ratio could be approximately 0·005%.

With reference to Mr. Hawkes's comments on Section 2.4.1, we would emphasize that the transformers referred to there are in no sense employed as 'absolute' transformers. In the one case the transformer merely provides arbitrary ratio arms for convenience in intercomparing the ratios and phase angles of two capacitance dividers at successively higher voltages. The test for changes with voltage referred to in the third paragraph of Section 2.4.1 is based on the observation that in a good transformer the ratio and phase angle plotted as functions of voltage are smooth curves. Onset of corona in the high-voltage capacitors is easily recognized as a sharp change in the shape of the plot, especially in the case of phase angle.

We agree with Mr. Felton that work along the lines suggested should be carried out, particularly in the case of high-voltage transformers, in which capacitance effects would be more pronounced.

In reply to Mr. Webb, we have had limited experience with the circuit referred to for measuring the secondary voltage of a testing transformer, but we feel that an accuracy limit of at least 1 part in 10^3 would arise in the measurement of tertiary voltage alone if this is done with an indicating instrument. We do not think much would be gained by the use of our circuit solely for this application, though it could readily be adapted for the purpose. On fundamental grounds, however, we prefer to take measurements of peak voltage directly on the high-voltage secondary.

We are much impressed with the simplicity and economy of Mr. Bowdler's method of measurement, having as it does some of the properties and advantages of a substitution method.

We have had no difficulty in obtaining a good detector balance, even when testing transformers working at high flux density, contributing reasons no doubt being that the detector amplifier provides third-harmonic attenuation of approximately 3 000 relative to the fundamental, and that we use a cathode-ray oscillograph indicator which makes it possible to observe the balance of the fundamental in the presence of a certain amount of residual harmonic.

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Paper No. 2165 M
Sept. 1956

THE MEASUREMENT OF EARTH-LOOP RESISTANCE

By G. F. TAGG, B.Sc., Ph.D., F.Inst.P., Member.

(*The paper was first received* 17*th March, and in revised form* 14*th June*, 1956. *It was published in September*, 1956, *and was read before* THE INSTITUTION 6*th December*, 1956, *and the* NORTH-WESTERN CENTRE 8*th January*, 1957.)

SUMMARY

Regulation No. 507 in The Institution's Regulations for the Electrical Equipment of Buildings calls for a measurement of the earth-loop impedance and gives a method by which this can be done. Several instruments have been devised and are available to carry out this test, but all draw their testing current from the mains and are thus liable to serious errors. Records taken with a recording voltmeter show that in most cases there is already a voltage drop in the neutral conductor, which is varying continuously and rapidly. It is shown both theoretically and by practical tests that instruments of this character can have errors under these conditions amounting to 100% or more. Any instrument intended to carry out these tests must be such that it will give the correct value despite the presence of the continuously varying voltage drop in the neutral. An instrument is described which draws its testing current from its own hand-driven generator and is free from these errors. The Regulation also calls for a measurement of impedance, but it is suggested that in most cases the difference between impedance and resistance of an earth loop is so small that an instrument measuring resistance will be sufficient.

(1) INTRODUCTION

In the thirteenth edition of The Institution's Regulations for the Electrical Equipment of Buildings certain statements are made concerning the impedance of the earth loop and its measurement. Regulation 507 states that '. . . each completed installation and, if possible, each final sub-circuit shall be tested by means of an earth-fault-loop impedance tester of the current-injection type'. The note attached to the Regulation states:

> The plug or terminal of the tester should connect it to the neutral and earth points, so that injected current (at a voltage not exceeding 40 volts) traverses the loop formed by the earth-return path, the earthing point of the supply neutral, and the neutral conductor. It is preferable for the current used in the test to approach 1½ times the rating of the sub-circuit, but in no instance need it exceed 25 amperes. The ratio voltage/current may be taken as the total earth-fault-loop impedance. . . . A diagram illustrating a method of earth-fault-loop testing using simple equipment is given in Fig. 1 on page 70.

The diagram is reproduced here, also as Fig. 1.

This simple method of measurement has been described,[1] and there are now available a number of instruments which are claimed to be capable of carrying out this test; it is the purpose of the paper to discuss the difficulties encountered in making the measurement and the instruments available for carrying it out.

(2) PRELIMINARY CONSIDERATIONS

When a fault to earth occurs in a consumer's premises, the fault current flows through the following path:

- Secondary winding of supply transformer.
- Line conductor.
- Fault.
- Consumer's earth-continuity conductor.
- Consumer's earth.
- Body of earth between consumer's earth and substation earth.
- Substation earth.

This is an 'integrating' paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

Dr. Tagg is with Evershed and Vignoles, Ltd.

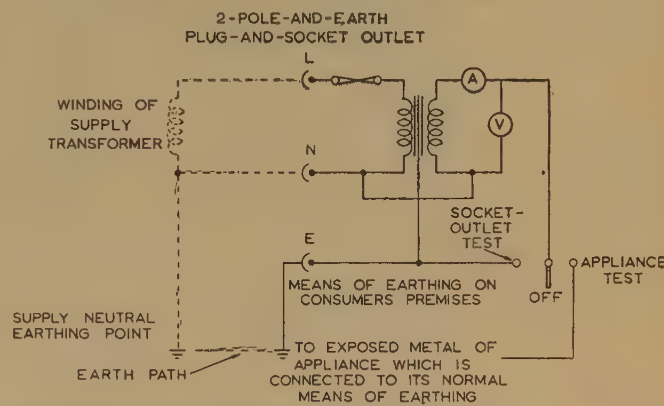


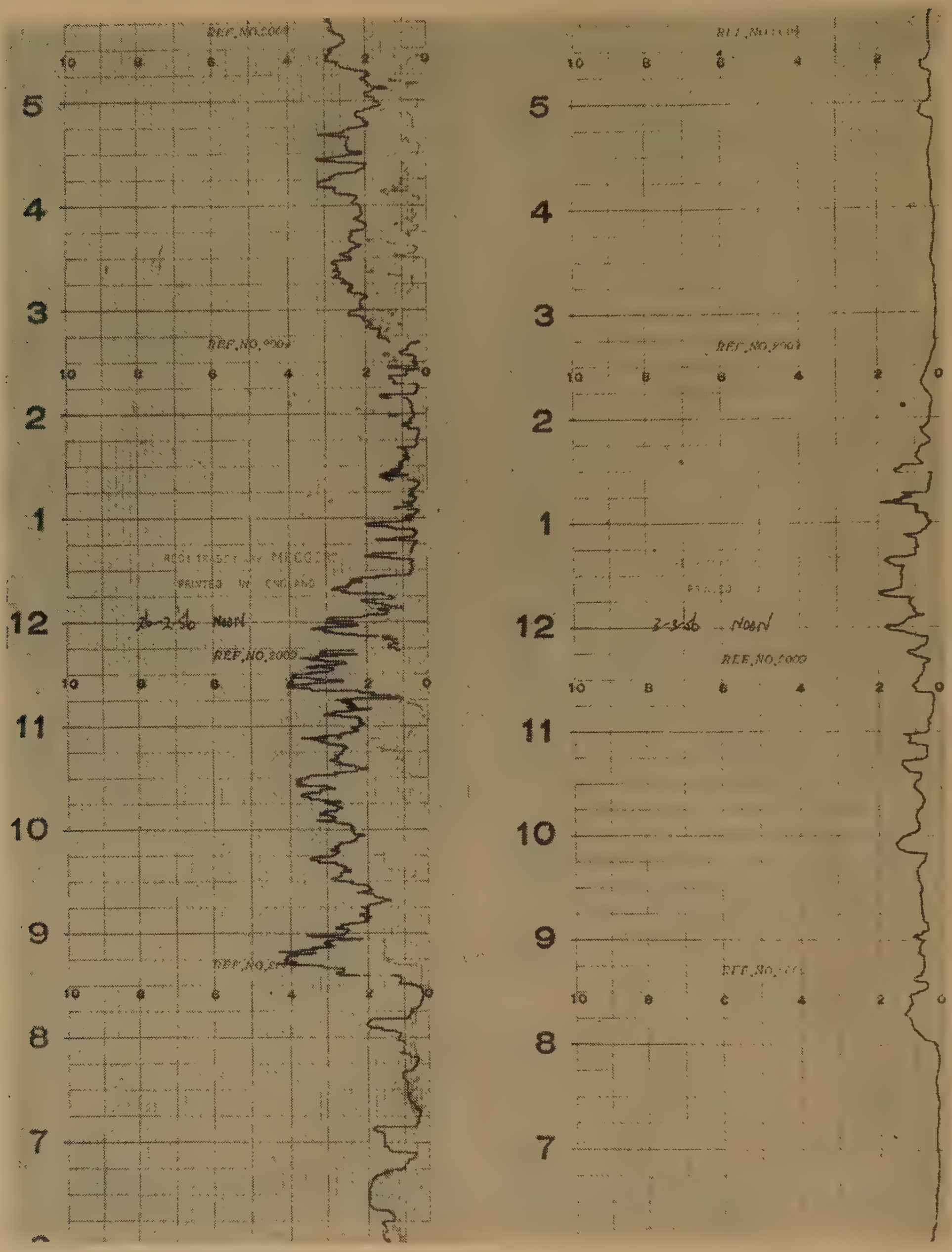
Fig. 1.—Current-injection system.
(From The Institution's Wiring Regulations.)

In the circuit shown in Fig. 1 the test current flows through the following path:

- Neutral conductor.
- Consumer's earth-continuity conductor.
- Consumer's earth.
- Body of earth between consumer's earth and substation earth.
- Substation earth.

In comparing these two circuits it is first necessary to assume that the fault is a complete one, i.e. of zero resistance. It is then clear that there are two main differences in the two paths. First, the test path includes the neutral conductor, while the fault path includes the line conductor. This does not matter if these conductors have the same cross-section and hence the same resistance, but this is not always the case. Secondly, the test path does not include the secondary of the transformer, and the amount this contributes to the impedance of the fault path is unknown. It is manifestly very difficult to make any test using the injected-current method, in which the line conductor and the transformer winding are included, and the substitution of the neutral conductor for the line conductor and the omission of the transformer winding must be accepted.

The fact that the neutral conductor is included in the loop introduces a further difficulty. The neutral conductor is probably shared by a number of consumers, and as a result will probably be carrying a current which may in certain cases be considerable. This means that there will exist between the connection to the neutral conductor and the connection to the earth-continuity conductor a voltage due to the passage of this current. In considering how to measure the loop impedance it is therefore necessary to remember that this impedance already has an unknown voltage drop in it. Moreover, not only is this voltage drop unknown, but it is also subject to very rapid variations both in magnitude and phase. This is illustrated as regards magnitude by the records shown in Fig. 2, which were taken by a recording voltmeter connected between neutral and earth. Fig. 2(*a*) was obtained at a house in Hampton, and shows very rapid variations, the maximum obtained being just over 4 volts. Fig. 2(*b*) was



(*a*) (*b*)

Fig. 2.—Neutral-earth voltage variations.

obtained at a house in Egham, and here the maximum voltage and the variations are somewhat less.

The fact that this voltage drop can cause an error has evidently been recognized by the manufacturers of some of the instruments available, since it is quite usual for the instructions to include a statement that the polarity of the testing current should be reversed, two readings taken and the mean accepted as the true value. Even if the voltage drop in the neutral remained constant during the test, this would not give the correct answer, the reason being shown later. The fact that the voltage drop is varying continuously makes matters worse. It is clear that, if an instrument is to give the correct result, it must be such that its readings are quite unaffected by a continuously varying voltage drop in the neutral.

Another point which has been rather laboured is the measurement of impedance instead of resistance. The use of the term 'impedance' implies that the circuit contains resistance and reactance, and the latter in this case would be inductive. Of the various components of the path of the test current, the ones most likely to contain inductance are the consumer's earth-continuity conductor and the neutral conductor. The former may include lengths of steel conduit and so may possess a small inductance; the latter may be rather long and may also have a small inductance, but it is doubtful whether the total inductance is sufficient to make an appreciable difference between the resistance and the impedance of the earth loop.

If a radio-interference-suppression choke or the primary of a measuring transformer is included in the loop, this may contribute a small inductance. It would appear that this will be of importance only when the loop resistance is very low, so that a

test would show it to be satisfactory. With higher loop resistances of such an order that a fuse would not rupture, the effect of this inductance would be negligible.

(3) THE VOLTMETER-AMMETER METHOD

The voltmeter-ammeter method can be shown simply as in Fig. 3, in which R_x represents the resistance of the earth loop

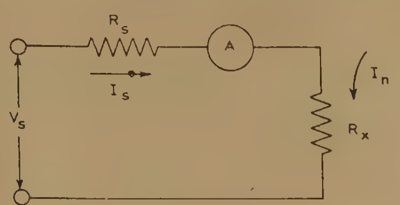


Fig. 3.—Voltmeter-ammeter method.

and R_s the internal resistance of the testing set. The latter applies a voltage V_s to the circuit, producing a current I_s which is registered by the ammeter A, while the loop resistance R_x is already carrying a current I_n. Now it follows that

$$I_s = \frac{V - I_n R_x}{R_s + R_x}$$

In most of the instruments using this principle the voltmeter is omitted and the ammeter is scaled directly in ohms, an inverse scale. For calibration purpose then, with $I_n = 0$ the condition is $k/I_s = R_x$, where k is the calibration constant, i.e.

$$k = \frac{V_s R_x}{R_s + R_x}$$

The reading, y, obtained in the general case will then be

$$y = \frac{V_s R_x}{R_s + R_x} \frac{1}{I_s}$$

Now consider the fact that the current I_n already flowing in the loop may have any phase relative to the testing voltage and so may be of the form $\alpha + j\beta$. The current I_s is then in the form

$$I_s = \frac{(V_b - \alpha R_x) - j\beta R_x}{R_s + R_x}$$

and since the instrument responds to the r.m.s. value of the current, the current producing the reading is

$$I_s = \frac{[(V_s - \alpha R_x)^2 + \beta^2 R_x^2]^{1/2}}{R_s + R_x}$$

and the actual scale reading will be

$$y = \frac{V_s R_x}{R_s + R_x} \cdot \frac{R_s + R_x}{[(V_s - \alpha R_x)^2 + \beta^2 R_x^2]^{1/2}}$$

$$= \frac{V_s R_x}{[(V_s - \alpha R_x)^2 + \beta^2 R_x^2]^{1/2}}$$

This can be written in the form

$$\frac{y}{R_x} = \frac{V_s}{[V^2 - 2\alpha V_s R_x + \alpha^2 R_x^2 + \beta^2 R_x^2]^{1/2}}$$

Now if V_n is the voltage drop in the neutral due to the current I_n, then $V_n^2 = (\alpha^2 + \beta^2) R_x^2$; furthermore, if ϕ is the phase difference between this voltage drop and the testing voltage V_s, then $\alpha R_x = V_n \cos\phi$. Then

$$\frac{y}{R_x} = \frac{V_s}{[V_s^2 - 2V_s V_n \cos\phi + V_n^2]^{1/2}}$$

$$= \frac{1}{\left[1 - 2\frac{V_n}{V_s}\cos\phi + \left(\frac{V_n}{V_s}\right)^2\right]^{1/2}}$$

Let $V_n/V_s = n$; then

$$\frac{y}{R_x} = \frac{1}{[1 - 2n\cos\phi + n^2]^{1/2}}$$

If now a second reading is taken with the polarity of the testing voltage reversed, it can be shown that this ratio becomes

$$\frac{y}{R_x} = \frac{1}{[1 + 2n\cos\phi + n^2]^{1/2}}$$

It is stated that the mean of these two values should be taken as the loop resistance. A number of calculations have been

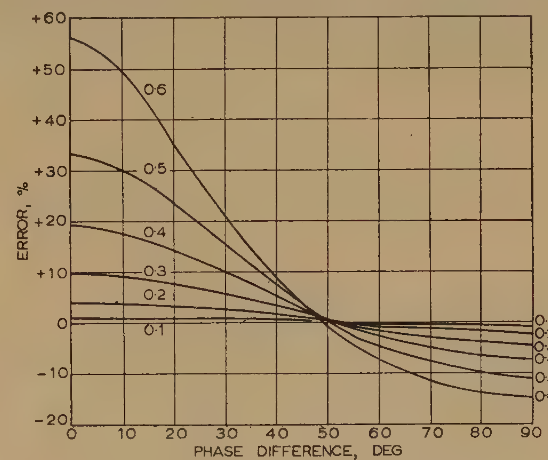


Fig. 4.—Errors in voltmeter-ammeter method.

The figures against the curves are the values of n.

based on these considerations and the results are given in Fig. 4. It will be seen that very large errors can arise with quite low voltage drops in the neutral conductor.

(4) THE BRIDGE METHOD OF MEASUREMENT

The fundamental diagram of this system is shown in Fig. 5. It consists of a normal Wheatstone bridge, in which R_x is the

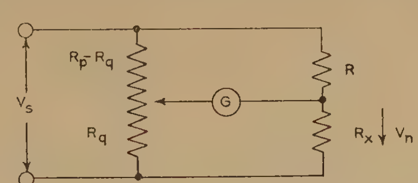


Fig. 5.—Bridge method.

loop resistance under test, R is a fixed resistance and R_p is a resistance divided into two parts, R_q and $(R_p - R_q)$, by an adjustable tapping. G is the balance galvanometer of the bridge and is an a.c. ammeter. The instructions with the instrument state that the tapping should be adjusted until the ammeter gives a minimum indication. The adjustable resistance is calibrated to read directly, and the reading is taken for minimum indication on G. The polarity of V_s is then reversed and the balance readjusted if necessary, the new reading being noted. The mean of the two readings is taken as the loop resistance. The loop

again contains the neutral conductor and may have in it a voltage drop V_n due to the current flowing in it.

The full analysis of this system is rather complicated, but it can be shown that the current through the balance indicator G is given by the expression

$$I_g = \frac{(a - bR_q) + cVn}{d + fR_q - gR_q^2}$$

where $a = VR_xR_p$

$b = V(R_x + R)$

$c = R_pR$

$d = R_pRR_x$

$f = R_p(R_x + R)$

$g = R_x + R$

The voltage drop in the neutral conductor may have any value and be of any phase relative to the testing voltage V_s, and so in the general case must be put in the form $\alpha + j\beta$. This then leads to an expression for I_g as follows:

$$I_g = \frac{(a - bR_q + c\alpha) + jc\beta}{d + fR_q - gR_q^2}$$

This is the vector expression for I_g, and the balance indicator shows the r.m.s. value of this current. The value indicated is then

$$I_g = \frac{[(a - bR_q + c\alpha)^2 + c^2\beta^2]^{1/2}}{d + fR_q - gR_q^2}$$

and R_g is adjusted to make this a minimum.

The calculations involved in determining the value of R_q to give a minimum value of I_g for various values of R_x and V_n are very complicated, and it is not proposed to give any details of these. A number of cases have been calculated and the results are given in Table 1. In this all resistances are expressed as fractions of the resistance R_p, and the two components α and β of the voltage drop in the neutral are expressed as fractions of the testing voltage V_s.

Table 1

R_x/R_p	R/R_p	α/V_s	β/V_s	Error
				%
0·5	0·5	0·2	0·2	−16·22
0·5	0·5	0	0·4	0
0·2	0·5	0	0·4	−13·1
0·2	0·5	0·4	0	0
0·2	0·5	0·5	0·5	+48·6
1·0	0·5	0·5	0·5	−2·62
1·0	0·5	1·0	1·0	−10·54
0·1	0·5	1·0	1·0	+195·4
0·1	1·0	1·0	1·0	+449·5
0·1	1·0	0·2	0·2	+176·0

An examination of this Table suggests that while large errors are possible in some instances, in general the errors are not so high as with the voltmeter-ammeter method. The difficulty remains, however, that in using any method of measurement which is liable to error, no reliance can be placed on the result when the extent of the error is unknown.

(5) REVERSED D.C. INSTRUMENTS

Another form of instrument which is used for this test differs in its operation from those previously described in that it does not draw its operating current from the mains but from a self-contained hand-driven generator. The direct current passed through the resistance under test is periodically reversed, and hence the instrument measures resistance and ignores any inductive reactance in the circuit. A diagram of a typical instrument is given in Fig. 6.

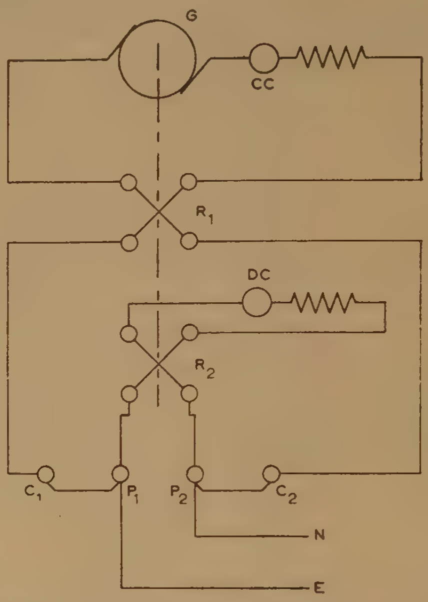


Fig. 6.—Circuit of reversed d.c. instrument.

Direct current from the hand-driven generator G passes through the control coil CC of a moving-coils ohmmeter, to a reversing commutator R_1 mounted on the generator spindle, and thence to the terminals C_1 and C_2 of the instrument and through the earth loop. The current actually traversing the earth loop is thus reversed direct current, and produces a voltage drop of a similar nature. This voltage drop is applied to the terminals P_1 and P_2 of the instrument and produces a current through the deflecting coil, DC, of the moving-coils ohmmeter, this current being first rectified by a second reversing commutator R_2 also mounted on the generator spindle and running in synchronism with R_1.

The position taken up by the moving system of a moving-coils ohmmeter, and hence the indication on the scale, is dependent only on the ratio of the currents flowing in the two coils. In this case one coil is carrying the testing current and the other a current proportional to the voltage drop across the resistance under test. The ratio of these currents is obviously this resistance, and the instrument is accordingly calibrated to read the resistance directly.

The frequency of reversal of the current is under the control of the operator, since it depends on the speed at which the handle is turned. The voltage drop already existing in the neutral conductor will tend to pass currents through both circuits of the ohmmeter. These currents are of power frequency and are rectified by the reversing commutators. If the latter are running at some frequency other than the power frequency, the net rectified current is zero and the instrument is unaffected by the presence of the voltage drop in the neutral conductor, which can accordingly vary in phase and magnitude during the test without producing an error. When a test is made the pointer of the instrument may waver, showing that the frequency of reversal is too near the frequency of the power currents; it is then necessary to increase the handle speed and consequently the frequency of reversal until the pointer is steady.

The waveform of the testing current is approximately rect-

angular, but the circuit conditions are not those in which a rectangular wave of voltage is applied to a circuit, since no permanent phase shift in the current is possible. This is due to the fact that the circuit is definitely broken twice in every cycle by the reversing commutators, so that the current is forced to zero during these breaks. It can be shown both by analysis and actual test that these instruments will measure resistance only and will ignore any reactance in the circuit.

(6) LABORATORY METHODS

In order to determine the accuracy of the various instruments it is necessary to have some means of measuring the earth loop with precision independently of the voltage drop which may already exist in the neutral conductor. Two methods have been devised for this purpose. The first of these is as follows. Suppose that the loop to be measured can be considered as consisting of a resistance R_x and an inductive reactance X and to be already carrying a current I_n, all as shown in Fig. 7. Suppose also that

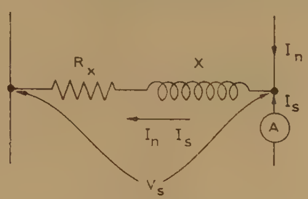


Fig. 7.—Fundamental circuit.

a testing voltage V_s applied to the loop will itself produce a current I_s. Then the total current in the loop will be $(I_n + I_s)$. The relative phase of the current I_n and the voltage V_s is unknown, so assume that the voltage must be represented by $V_s(a + jb)$. Then

$$V_s(a + jb) = (R_x + jX)(I_n + I_s)$$

i.e.

$$I_s = \frac{(V_s a - IR_x) + j(bV_s - I_s X)}{R_x + jX}$$

Now if both the magnitude and the phase of V_s can be altered, it should be possible to reduce the indicated current I_s to zero. This will occur when $V_s a = I_n R_x$ and $V_s b = I_n X$ or $a = I_n R_x / V_s$ and $b = I_n X / V_s$.

Let this value of V_s be V_0, so that

$$a = I_n R_x / V_0 \text{ and } b = I_n X / V_0$$

Now suppose the voltage is increased to nV_0, the phase remaining unchanged.

Then the new voltage is

$$nV_0(a + jb) = nV_0\left(\frac{I_n R_x}{V_0} + \frac{jI_n X}{V_0}\right) = nI_n(R_x + jX)$$

so that the new current is

$$I_s = \frac{nI_n(R_x + jX) - I_n(R_x + jX)}{R_x + jX} = (n - 1)I_n$$

The measured value of the new voltage is $nI_n\sqrt{(R_x^2 + X^2)}$

The measured value of the original voltage $= I_n\sqrt{(R_x^2 + X^2)}$

Therefore, the increase in measured voltage $= (n - 1)I_n\sqrt{(R_x^2 + X^2)}$

Thus:

$$\frac{\text{Increase in measured voltage}}{\text{Current}} = \frac{(n-1)I_n\sqrt{(R_x^2 + X^2)}}{(n-1)I_n} = \sqrt{(R_x^2 + X^2)}$$

which is the required loop impedance.

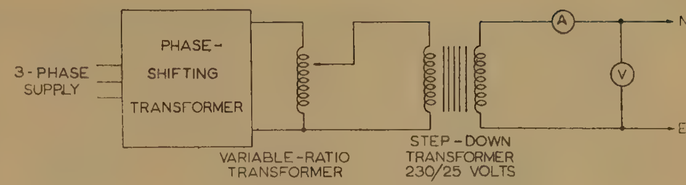


Fig. 8.—Laboratory method.

The circuit used for this measurement is shown in Fig. 8. By means of the phase-shifting and variable-ratio transformers the phase and magnitude of the voltage applied to the loop can be varied, the procedure being to adjust both until the ammeter reads zero, and then take the reading of the voltmeter. The phase is left unchanged and the voltage is increased by means of the transformer. The increase in voltage divided by the current then gives the required impedance.

A modification of this method is used when a phase-shifting transformer is not available, with the assumption that the inductive reactance can be ignored. Then, if I_n is the measured current passed into the loop and V_s is the voltage across it, with an existing voltage drop $\alpha + j\beta$ already in the neutral it follows that

$$I_n R_x = V_s - (\alpha + j\beta) = (V_s - \alpha) - j\beta$$

and in terms of measured r.m.s. values

$$I_n^2 R_x^2 = (V_s - \alpha)^2 + \beta^2 = V_s - 2\alpha V_s + \alpha^2 + \beta^2$$

$\alpha^2 + \beta^2 = V_n^2$, where V_n is the value of the voltage drop in the neutral. If a series of simultaneous readings of V_s and I_n are taken, the value of R_x, α and V_n can be deduced by using this equation and the method of least squares.

(7) TESTING CURRENT

Regulation 507 suggests a testing current approaching 1½ times the fuse rating, and there does appear to be a certain amount of evidence that currents of the order of amperes should be used for this test. This is the basis of one criticism which has been made of the reversed d.c. instruments, since the currents they deliver are measurable in milliamperes. In order to meet this criticism, another instrument capable of delivering a higher current was constructed. The maximum power obtainable from the hand-driven generator is about 30 watts, and a generator wound for 10 volts would give a maximum current of 3 amp. The ohmmeter used was given a range of 0–10 ohms, which later tests showed to be too low, and the approximate currents delivered were

Resistance under test, ohms	*Current, amp*
0	3·0
1·0	2·3
2·0	1·87
5·0	1·58
10·0	0·75

(8) INSTRUMENTS USED IN PRACTICAL TESTS

The instruments used in the practical tests were as follows:

(*a*) Instrument A.—Reversed d.c. instrument as described in Section 7, range 0–10 ohms.

(*b*) Instrument B.—Reversed d.c. instrument, ranges 0–20 and 0–200 ohms.

(*c*) Instrument C.—Reversed d.c. instrument, ranges 0–40 and 0–200 ohms.

(*d*) Instrument D.—Earth-loop impedance tester, range 0–5 ohms. (This is an instrument working on the voltmeter-ammeter principle, but with no voltmeter and the ammeter scaled in ohms.)

(*e*) Instrument E.—Earth-loop resistance tester, range 0–30 ohms. (This works on the bridge principle.)

(*f*) Equipment to enable the tests described in Section 6 to be carried out.

Table 2

Test Number	Measured voltage, between neutral and earth	Instrument readings C	Instrument readings D	Instrument readings E	Laboratory measurement
	volts	ohm	ohms	ohm	ohm
1	1·00		1·09	0·41	
2	1·00		1·11	0·47	
3	1·70	0·56	1·09	0·54	
4	1·80	0·56	1·09	0·54	
5	1·00	0·56	1·05	0·43	
6	1·13	0·56	1·06	0·48	
7	1·88		1·13	0·53	
8	1·16		1·00	0·43	
9	1·65		1·10	0·53	0·551
10	1·40	0·56	1·02	0·45	
11	1·77		1·10	0·43	
12	1·51		1·13	0·49	
13	1·45	0·57	1·15	0·46	0·541
14	2·37	0·56	1·21	0·55	0·544
15	1·66		1·15	0·48	
16	1·52		1·06	0·55	
17	1·59		1·09	0·50	
18	1·78		1·16	0·48	
19	2·14		1·23	0·64	
20	1·44		1·08	0·48	
21	1·48	0·57	1·18	0·55	0·542
22	1·32		1·15	0·49	
23	1·70		1·16	0·47	

(9) PRACTICAL TESTS

A series of tests have been made with the various instruments. The first were made from a 3-pin plug in a research laboratory, and all the instruments mentioned in Section 8 were not available. The results of these tests are given in Table 2. The laboratory measurements in this Table were made by the first method described in Section 6 and illustrated in Fig. 8. It will be seen at once that instrument D gives completely wrong readings, the errors amounting to nearly 100%. Instrument E gives results varying from 0·41, which is 32% low, to 0·64, which is 18% high. Instrument C gives a consistent value which agrees fairly closely with the more accurate laboratory measurement. The Table also includes the p.d. between neutral and earth, which varied from 1·0 to 2·37 volts; the phase of this voltage was not ascertained.

An interesting point which arises from this series of tests is the close agreement between the reversed d.c. instrument and the laboratory measurement. Since it is known that the former instrument measures resistance, while the latter measurement is that of an impedance, it follows that any inductance in this particular loop was negligible.

This tends to confirm the assumption made in Section 2 that the loop can be treated as having resistance only.

The results of a more extended series of tests are given in Table 3. In these tests additional resistance was added to the loop, so that measurements could be made on three different resistances. The total values are given in parenthesis at the tops of the columns. The third value (10·18 ohms) was too high for instrument D, which has a range of 0–5 ohms only. Some slight variations in values observed are to be expected in this case, since the experimental arrangement contained at least two plug connections.

It will be seen, however, that instrument D again has very large errors, that instrument E has smaller errors, and that the reversed d.c. instruments A, B and C give consistent values very close to the true value.

As a matter of interest a number of measurements were made by the second method described in Section 6, mainly with a view to obtaining information on the value and relative phase of the voltage drop in the neutral. The results are given in Table 4.

The next set of tests were made at a house in Hampton, when the voltage drop in the neutral was varying continuously and rapidly as already shown in Fig. 2. This continual and rapid

Table 3

Test number	Voltage between neutral and earth	Direct connection A	Direct connection B	Direct connection C	Direct connection D	Direct connection E	With 3 ohms in series (3·43) A	B	C	D	E	With 10 ohms in series (10·18) A	B	C	E
	volts	ohm	ohm	ohm	ohms	ohm	ohms	ohms	ohms	ohms	ohms	ohms	ohms	ohms	ohms
1	0·92	0·5	0·56	0·56	1·2	0·45	3·55	3·6	3·6	5·0	3·6	10·5	10·7	11·0	8·4
2	1·05	0·55	0·54	0·54	1·2	0·50	3·50	3·6	3·3	5·0	3·5	10·3	10·7	10·5	9·0
3	1·83	0·54	0·53	0·53	1·2	0·51	3·40	3·6	3·3	4·75	3·6	10·3	10·8	11·0	8·6
4	0·92	0·51	0·55	0·52	1·2	0·45	3·4	3·6	3·3	5·0	3·6	10·3	10·8	11·0	9·35
5	1·10	0·51	0·51	—	1·1	0·50	3·4	3·6	—	4·9	3·3	10·3	11·0	—	8·75
6	2·20	0·51	0·55	—	1·19	0·59	3·5	3·6	—	4·9	3·6	10·3	11·0	—	8·85
7	1·15	0·51	0·53	0·50	1·2	0·48	3·5	3·6	3·5	5·0	3·35	10·3	11·0	11·0	9·35
8	1·84	0·56	0·58	0·50	1·14	0·54	3·5	3·6	3·5	4·9	3·35	10·3	11·0	11·0	9·85
9	1·12	0·53	0·53	0·50	1·2	0·54	3·4	3·6	3·5	5·0	3·6	10·3	11·0	11·0	9·6
10	2·46	0·52	0·52	0·50	1·2	0·55	3·4	3·6	3·5	5·0	3·3	10·3	11·0	11·0	9·1
11	1·03	0·52	0·52	0·50	1·09	0·51	3·4	3·6	3·5	4·9	3·15	10·3	11·0	11·0	8·15
12	1·38	0·54	0·53	0·50	1·09	0·56	3·5	3·6	3·5	4·9	3·45	10·3	11·0	11·0	8·7
13	0·87	0·49	0·50	0·42	1·10	0·48	3·4	3·6	3·5	4·9	3·35	10·2	10·9	11·0	9·85
14	1·32	0·53	0·50	0·40	1·12	0·47	3·4	3·6	3·4	5·0	3·35	10·3	11·0	11·0	9·6

Table 4

Test number	Loop impedance	Voltage drop in neutral	Phase relative to testing voltage	
	ohm	volts	deg	min
1	0·548	0·548	43	34
2	0·521	1·240	45	15
3	0·536	1·898	23	44
4	0·549	1·039	71	43
5	0·489	2·151	37	44
6	0·513	0·447	15	43

variation made it impossible to carry out the more accurate methods of measurement described in Section 6, for although these will deal with a voltage drop in the neutral conductor, the drop must remain constant during the test. The values obtained are given in Table 5.

Table 5

Test number	Instrument reading				
	A	B	C	D	E
	ohm	ohm	ohm	ohms	ohm
1	0·75	0·75	0·73	1·20	0·75
2	0·80	0·90	0·90	1·81	0·95
3	0·70	0·80	0·72	1·54	0·85
4	0·85	0·90	0·88	1·15	0·60

Again the reversed d.c. instruments A, B and C agree fairly well with one another; instrument D has a large error and instrument E has smaller errors.

Tests were also made at a house in Englefield Green; it was not possible to take the apparatus for the laboratory type of measurement, but the results obtained with the other instruments are given in Table 6.

Table 6

Test number	Instrument reading				
	A	B	C	D	E
	ohm	ohm	ohm	ohm	ohm
1	0·55	0·60	0·55	0·81	0·55
2	0·55	0·58	0·55	0·87	0·55

Again, instruments A, B and C agree with one another; D has a large error, but E agrees with A, B and C.

The tests so far described have been carried out on premises fed by underground cable and are such that low-resistance loops are to be expected. A more difficult case would be probably one in which the supply enters by an overhead line. The instruments were therefore taken to a manor house in Great Mongeham, near Deal, which is fed in this way; tests were made there on the earth loop and some interesting points emerged immediately.

The measurements were made on the 1st February, 1956, and the first thing noted was that the voltage drop in the neutral was high: it was 14·76 volts at 12.30 p.m., 12·09 volts at 1.50 p.m., 10·98 volts at 2.30 p.m., and 11·46 volts at 3.30 p.m. The first measurements taken were made with the instruments B and C, both giving a value of 26 ohms (this was noted by two observers, so that there is no possibility of mistake). This value is beyond the range of any of the other instruments, except E, which has a range of 0–30 ohms, but the test made with this gave the surprising value of 1·45 ohms. Instruments D and A were then used and gave 1·01 and 1·40 ohms respectively. Finally a repeat test was made with instruments B and C and these gave 1·40 and 1·80 ohms respectively.

In these tests the earth-continuity conductor was taken to a clip round a water pipe, and there appears to be no doubt that this was a bad connection in that a film formed between the clip and the pipe. The low current delivered by instruments B and C was insufficient to break this down, with the result that they gave the high value of 26 ohms. The heavier current (5 amp) delivered by instrument E broke down this film and gave the value of 1·45 ohms, and the resistance remained at this level for the subsequent tests. This is evidence in support of the contention that these measurements should be made with a comparatively heavy current.

It will be seen again that instrument D had a large error, but that instrument E agreed with instruments A, B and C.

Finally tests were made at a barn in the neighbourhood fitted with grain-drying and storing equipment, with the following results:

	ohms
A	9
C	9
E	7·7

The voltage between neutral and earth was 1·3 volts.

Instrument E has an error compared with A and C, and this is the first case encountered where the loop resistance is too high to enable a fuse to rupture in the event of a fault to earth.

(10) OTHER METHODS

Two other methods have been described recently. One is due to Baggott,[2] and in essence his circuit for measuring the loop resistance is shown in Fig. 9. In this the testing voltage, V,

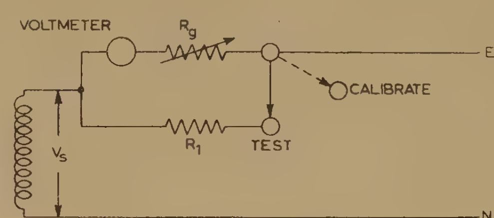


Fig. 9.—Baggott's method.

obtained from the secondary of a transformer, is connected in series with the earth loop. A voltmeter calibrated in ohms is connected in series with an adjustable resistance R_g, and by means of a switch can be connected across the circuit consisting of the transformer secondary and the earth loop, or can be so connected with a shunt R_1 across it.

The procedure then is to set the switch in the position marked 'calibrate' and to adjust R_g until the voltmeter gives full-scale deflection. The switch is then moved to the position marked 'test' and the loop impedance is read directly from the scale.

Assume for the moment that the loop is an impedance $R_x + jX$ and that it contains a voltage drop $a + jb$. If V is the transformer secondary voltage, the total voltage in the circuit is $V + a + jb$. The current through the voltmeter is then $(V + a + jb)/R_g$. The indicated current is $[(V+a)^2 + b^2]^{1/2}/R_g$, and R_g is adjusted so that this is the full-scale value I_0. Then

$$R_g = \frac{[(V+a)^2 + b^2)^{1/2}}{I_0}$$

When testing, if it is assumed that R_g is large compared with R_1, the circuit impedance is $R_1 + R_x + jX$, the total current is

$$\frac{V + a + jb}{R_1 + R_x + jX}$$

The current through the voltmeter is

$$\frac{(V + a + jb)}{(R_1 + R_x + jX)} \frac{R_1}{R_g}$$

and the indicated current is

$$I = \left[\frac{(V+a)^2 + b^2}{(R_1 + R_x)^2 + X^2}\right]^{1/2} \frac{R_1}{R_g}$$

Substituting for R_g gives

$$I = \frac{R_1 I_0}{[(R_1 + R)^2 + X^2]^{1/2}} \text{ or } \frac{I}{I_0} = \frac{R_1}{[(R_1 + R_x)^2 + X^2]^{1/2}}$$

If now X can be assumed to be negligible, then

$$\frac{I}{I_0} = \frac{R_1}{R_x + R_1}$$

and the scale can be calibrated to read R_x directly. Certain refinements are included such as a correction for the regulation of the transformer. The following conclusions can be drawn from this analysis:

(*a*) The voltage drop in the neutral conductoı must remain constant during the test (see Fig. 2).

(*b*) The instrument can be calibrated to measure resistance, but not impedance. As already stated, it is probable that most earth loops can be treated as having resistance only.

One obvious but possibly inconvenient way of testing the earth loop is to determine whether the fuse will actually rupture, which is the basis of a method proposed by Roscoe.[3] This instrument has been designed to apply a fault current of predetermined magnitude for a limited period of approximately 0·01–0·02 sec using a high-speed circuit-breaker. A series of resistors whose combined value is determined by the current rating of the fuse to be tested are momentarily connected in turn between phase and earth. The first resistor is a filament lamp which flicks in to prove that the loop impedance is continuous and safe for the test to proceed. A voltage relay is connected across the resistors and operates if a certain predetermined current flows equal to twice the current rating of the fuse to be tested. The operation of this relay closes its contacts and lights a neon lamp, indicating that the minimum value of current has actually flowed. Before starting the test a voltage rheostat is set to the measured voltage of the supply to ensure the correct voltage across the operating coil of the relay.

With this arrangement, no indication is given of the actual loop impedance, and there is no way of finding out whether there are any bad contacts such as films in the circuit.

(11) CONCLUSIONS

As a result of the above work the following conclusions have been reached:

(*a*) Any instrument which is to carry out this test and give the correct result must be completely unaffected by an existing voltage drop in the neutral conductor, which is varying continuously and rapidly in both magnitude and phase.

(*b*) It should be possible to carry out tests at two currents, one of the order of 100 mA and the other of the order of a few amperes, so that bad-contact conditions can be detected.

(*c*) From both theoretical investigation and practical tests, those instruments which operate on the volt-ammeter method, or a modification of it, are liable to considerable error when a voltage drop already exists in the neutral.

(*d*) The same comment applies to those instruments which use a bridge method of measurement, although it appears that in most cases the errors will not be so high.

(*e*) Instruments using the reversed d.c. method appear to give correct results, provided that the loop can be considered as having resistance only.

The latest form of reversed d.c. instrument will have a range of 0–50 ohms (semi-logarithmic scale), together with facilities for making tests at currents of about 300 mA and of 2–3 amp.

(12) ACKNOWLEDGMENT

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DISCUSSION BEFORE THE INSTITUTION, 6TH DECEMBER, 1956

Mr. H. W. Swann: A few weeks before his death the late Mr. P. V. Hunter discussed loop testing with me at some length. He was convinced that loop testing is fundamentally a good thing, and he was glad that it had found a place in the 13th Edition of The Institution's Wiring Regulations, but he thought—and he knew of Dr. Tagg's paper—that there might be some danger of the purpose of loop testing being overlooked in the pursuit of comparative accuracy, and he attached more importance to a safe margin for fuse operation. Most of the comparative readings are given at a range of about 0·5 ohm, but the agreement was much better when the author compared them at about 10 ohms; this is relevant to Mr. Hunter's point, because it is with resistances of 10 ohms and above that the importance of loop testing is most apparent.

The author mentioned Regulation 507 and the note appended which recommends that the testing current should be 1½ times the rated current for a circuit of 25 amp. At the prescribed voltage of 40 volts, a loop resistance of 40 ohms will allow a test current of only 1 amp, and this is independent of whether the instrument will give 25 amp. This leads to the question of the minimum testing current, and the author mentions the oxide film—a matter which gave me some concern a long time ago. A few milliamperes are insufficient to deal with oxide films, and the author has developed a set to work at 3 amp and 10 volts. I am still uncertain, however, whether we are any nearer a minimum testing current and whether, if there is such a constant, it should be stated in watts, volts or amperes.

In Section 6 the author says that he made tests by means of a phase-shifting transformer, which in some cases could not be adjusted to keep pace with the rapidity of the phase shift. This raises the question of which has the more important effect on accuracy—phase displacement or netral voltage. When the author recorded 13–14 volts in the neutral at Great Mongeham the instruments agreed fairly well at 1·4 ohms, and I imagine that the phase displacement was not great. Does the author attach more importance to displacement than to neutral voltage?

I think we are tending to give the wrong degree of importance to impedance as distinct from resistance. Many installations nowadays are of the plastic- or rubber-sheathed type, and I agree with the author on this point.

Finally, the author refers to other methods of testing, in particular Roscoe's test, which, I think, consists in putting an actual fault on a system and seeing whether the fuse will blow. There is some merit in this method, if only because if there is no measurement there can be no disagreement about it.

Mr. J. Hall: From an installation engineer's viewpoint the results in Table 2 are very disturbing. Column D gives the impedance test taken in accordance with Regulation 507, and it appears that calculations made on the current that will flow on fault can err by nearly 100%. Regulations up to and

including the 11th Edition required the resistance of the earth-continuity conductor, but the 12th Edition (1950) substituted impedance for resistance. Installation engineers found it impracticable to carry out these impedance tests to give worth-while results, and, furthermore, were unable to obtain suitable testing sets from manufacturers. There are also some doubts as to whether certain sets now available to carry out the impedance tests actually meet the requirements of the present Regulations, since the current injected into the loop should approach 1½ times the rating of the sub-circuit, and this is not possible in a number of sets.

In Table 2, calculations on the fault current that will flow in accordance with Column D will approximate to half that in Column C. The National Inspection Council will shortly be making tests on installations in accordance with Column D, and on these results a considerable amount of time and money will no doubt be spent in endeavouring to reduce impedances, and in some cases it may be necessary to install earth-leakage circuit-breakers after the installation has been completed. This may be quite unnecessary if Column C is correct.

Considerable difficulties have been experienced over the last few years in endeavouring to measure impedances; the author now says that these are unnecessary and only resistance is required. Installation engineers feel the time has come when it is necessary for the position to be clarified to avoid further difficulties, and they would willingly co-operate with those who draft the Regulations and with the instrument manufacturers to get the matter settled.

Mr. G. F. Shotter: I should like to confine my remarks to the use of the low-high-low current testing of the earth-continuity conductor and the earth loop. This type of test is based on the phenomenon associated with oxide films, whose resistance varies inversely with the current passed through them: an additional effect is that, after passing the higher current, the following low-current test will show approximately the same resistance as the high-current one, demonstrating that some form of welding has occurred. This test therefore indicates the condition of various joints in the earth-continuity conductor and the earth loop. The order of variation of resistance between the first low-current and the high-current tests, even with slight oxide films, is of the order of 100 : 1. The author quotes one case (Great Mongeham) when the ratio of resistance was 26 : 1·45. The earth clip and pipe were examined after the tests and found to be corroded. It should not be assumed, however, that the low resistance obtained in the high-current test would remain at this value.

On the choice of instruments for this type of test I should like to point out that, while the low-current instruments would show the high resistance in the case quoted, they would not indicate the possible cause, while the high-current instruments would show the low resistance and thereby, in the case of oxide films, give a false sense of security.

I should also like to emphasize that, where the oxide film is thick, the voltage required to break it down may exceed 240 volts; thus it does not follow that, under fault conditions, the film would break down sufficiently to allow the protection to operate.

Finally, I should like to support the author's contention that the measuring of the resistance of the earth loop is, in the majority of cases, sufficient; the instrument described in the paper would seem to make it possible for accurate tests to be carried out without the complication of neutral voltages.

I do not wish to minimize the importance of the reactance imposed by heavy-gauge conduit in increasing the total impedance of the loop circuit in certain circumstances, but it should not be over-emphasized.

Mr. T. C. Gilbert: I agree with the author regarding the accuracy of loop tests when the neutral is used, but from a rather more practical standpoint. Unless such tests are to be very misleading, the insulation against earth of the neutral must be impeccable; if there are dormant faults the testing current will be shunted over these paths, and may never reach the substation electrode. It has been reported that loop testing has been abandoned in at least one area for this reason, and it is difficult to visualize any area in which neutral faults are absent.

I am concerned about the author's contention that impedance is to a great extent of no significance, as this contradicts the findings of a recent E.R.A. Report, which indicates that 25 amp is a critical testing current and at that level impedance may, under fault conditions, be several times the resistance. As is usual in these considerations, the author has assumed that the fault impedance is zero, but we know that, in practice, faults exhibit resistance in their initial stages, and it seems important to secure isolation at that level. Testing loops with high or low currents appears to be unimportant unless we can overcome the fault-impedance factor; in fact, it would appear almost futile to attempt to achieve a true picture of what will happen under practical fault conditions with direct earthing. It would be far more rewarding to concentrate upon installation methods and systems not so liable to earth faults by greater use of double insulation, for instance, both in wiring and appliances, backed up where necessary by voltage-operated protection. At least with this method we have a simple form of test under working conditions, while the paper clearly demonstrates the inherent weaknesses of alternative methods. So long as we remain wedded to metalclad wiring systems and equipment where non-metallic alternatives would afford improved service we shall suffer the difficulties associated with testing earthing conditions.

Mr. C. E. Bedford: I became interested in these problems when I purchased 40 instruments to distribute through a country-wide maintenance organization, so that we could comply in our testing with the Wiring Regulations.

A prototype was left in a 15 amp sub-circuit for three weeks, and indicated readings were taken at regular intervals. During this period we found a variation in earth-loop impedance readings exceeding 2 : 1, while the maximum variation over half an hour was 1½ : 1. I agree that none of the readings was so high that the fuse protection of that circuit was inadequate. I feel, however, that if we are to have an instrument we can rely upon, we want one in which the man who is using it can have confidence: by this I mean, not a highly competent engineer, but an installation electrician who wants to know that the results he gets will be consistent.

The author's instrument thus has distinct advantages, and the two-current range has much to commend it. A testing current of 25 amp immediately breaks down the oxide film, and one is not aware that it was there. A test should determine whether there are any troubles or errors in the circuit, so that they can be rectified. With the two current ranges the low-current test immediately gives an indication that there may be something wrong with the circuit, while the higher-current test, breaking down the film, indicates where the resistance lies. One can then rectify the conditions that caused the film to form.

The loop test introduces a very interesting problem—the relationship between an installation contractor and a consulting engineer, or the customer. The installation contractor may produce a perfectly good installation, but the loop test may show that the earth-loop impedance or resistance is not what it should be; the customer, or the consulting engineer, is then faced with considerable additional expenditure to overcome the trouble, which does not lie at the contractor's door. Who pays?

I should be glad if the Regulations—to which we as an organization try to adhere most tenaciously on principle—permitted us to use an instrument such as the author describes. We could

depend upon it to give reasonably consistent results, it could be used by semi-skilled labour and the results would not need too much interpretation.

Mr. S. F. Knight: I should like to raise some points on the theory of the voltmeter-ammeter method and the corresponding tests on instrument D. Fig. 4, which gives the error curves for this method, shows that the errors may be positive or negative and that they vary widely with n. We are not told the value of V_s in the tests recorded in Tables 2 and 3, but V_n varies over a 3 : 1 range, so that n must vary by a similar amount. In spite of this the experimental error is remarkably constant, always positive and very high when instrument D is used to measure an impedance of about 0·5 ohm. The results seem to be completely at variance with the curves in Fig. 4.

When the instrument is used on a higher impedance, the error is much reduced. This would suggest that the instrument is out of adjustment and works better with higher impedances, and the author's comments on this would be welcome.

It would be helpful if Table 1 could be extended and the results given in the form of curves similar to Fig. 4. As it is, Table 1 is too meagre to allow any useful conclusions to be drawn from it.

Mr. R. G. Parr: It seems clear from measurements quoted in the paper and some made by the Electrical Research Association that, so far as domestic and similar installations are concerned, there is very little reactance in the circuit. Consequently, d.c. measurements agree as closely as one would expect with a.c. measurements. This is particularly true in rural areas, where the earth-electrode resistance is a fair portion of the total circuit resistance.

In large buildings, however, there may be runs of steel conduit some 200 ft or more long, with a d.c. resistance approaching 0·1 ohm. The a.c. resistance and reactance of conduit has been measured and some interesting results, together with a theoretical treatment, have been published in E.R.A. Report V/T111. In some circumstances it was found that the impedance was up to five times the d.c. resistance when measured with a current of 20–30 amp. A typical factory run, consisting of 90 ft of $\frac{3}{4}$ in conduit plus 60 ft of $1\frac{1}{4}$ in conduit, had a d.c. loop resistance of 0·7 ohm, with an impedance of 0·8 ohm at 5·8 amp and of 0·98 ohm at 16·4 amp.

Having regard to the substitution of the neutral for the phase conductor in some existing loop-testing techniques, we have made measurements of the neutral voltage and find that the phase angle may vary more than the magnitude. We have noted a phase-angle swing of 70° while little or no movement was noted on the voltmeter.

There is one important point about the neutral voltage which is not shown in Fig. 2. If the time-scale of this chart is 1 in/h, there is little distinction between neutral-voltage changes taking place in a second and those taking place in a minute. However, there is an important distinction from the measurement aspect between these two types of variation. An injection tester can be designed to take account of the neutral voltage, provided that the voltage remains constant for a short time while readings are taken. Lengthy observations have shown that, in fact, the neutral voltage is usually steady for a period of several seconds. Also, a sudden change which consists of an increase and an equal decrease after a few seconds is a rarity.

Fig. A illustrates a simple circuit which takes account of the neutral voltage. The neutral-conductor resistance is $R_a + R_b$ with other consumers' current, I_n, flowing in it. A voltage, V_A, is injected through a voltmeter with a short-circuiting switch and an ammeter and back through the earth-continuity conductor, etc., to the substation. The neutral voltage is V_N. The total voltage measured round the loop is V_L, which is the vector sum

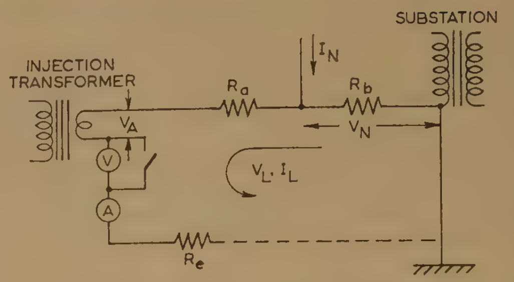

Fig. A.—Injection circuit to avoid errors from neutral voltage.

of V_N and V_A. If V_N remains constant in magnitude and phase, so also does I_L, and V_L/I_L will be the total loop impedance. A second test will provide a check.

Mr. G. F. Bedford: The Institution's Regulations on the testing of earth-loop impedance recommend the transformer type of test set referred to as instrument D, to which the author's objection appears to be the errors introduced into the results by the presence of a current in the neutral. Fig. 4 shows that, according to the phase displacement of the neutral current, these errors may be either positive or negative. In the Tables of test results all the discrepancies between instrument D and the other instruments are very much positive, usually about 100%. We are entitled to wonder whether the phase displacement of the neutral current was always such as to give rise to a positive error of such magnitude. The normal earth-loop circuit includes steel conduit, iron boxes, switchgear, and possibly cable sheaths and earth electrodes. With so much iron in the circuit it is possible that the impedance may vary with the current flowing.

The Tables do not give the approximate value of each injected current. Presumably instrument C will not give more than 3 amp. but instrument D, at an impedance of 1 ohm, normally injects about 15 amp.

Table 2 would be more informative with the following additions:

(*a*) The approximate currents at which these measurements were taken.

(*b*) Tests carried out with no current in the neutral.

(*c*) Tests carried out with all instruments on an artificial circuit of known impedance which will not change with increasing current; otherwise the variation of impedance with current may well give misleading results.

Life would be easier for the contractor with an instrument giving results twice as good as those given by the transformer type, but until such points are cleared he must still strive to comply with the Regulation in its present form.

Dr. G. L. d'Ombrain: The case made by the author against the earth-loop tester based mainly on the results embodied in Fig. 4 of the paper is misleading. The 13th Edition of the Wiring Regulations shows a diagram of such a tester, and reference to this will show that it is intended to use a voltmeter as well as an ammeter. The manufacturers of this equipment have dispensed with the voltmeter, presumably on the grounds of cost and of simplicity in use. Accordingly, they scale the instruments in terms of current and resistance, the latter being obtained by insertion of resistance externally, thus allowing for the regulation of the internal transformer, although not, of course, for mains variations. The manufacturer's instructions say that the resistance recorded on the scale should be measured for both directions of the injection voltage, and these results when averaged will give the earth-loop neutral resistance. Fig. 4 shows the results of such a procedure.

However, in my opinion the use of the instrument in this way is entirely incorrect; the correct procedure is to measure the current

for both directions of injection and to divide the mean of these two results into the open-circuit voltage of the transformer. The result is $K(R_s + R_x)$, where K is a correction factor, R_s is the equivalent internal resistance of the injection transformer and of the ammeter, and R_x is the earth-loop neutral resistance.

The value of K has been determined for some of the cases covered in the curves of Fig. 4, as follows:

n	K			
	$0 = 0°$	$0 = 30°$	$0 = 60°$	$0 = 60°$
0	1	1	1	1
0·1	1	1	1	0·99
0·5	1	0·98	0·91	0·89

where n, as in the paper, is the ratio between the neutral voltage drop due to currents other than the injection current and the injection voltage.

This puts the instrument in a very much more favourable light than that suggested by the author. It would seem that the manufacturers of these instruments have forgotten their elementary algebra, i.e.

$$\tfrac{1}{2}\left(\frac{1}{a} + \frac{1}{b}\right) \neq \frac{1}{\dfrac{a+b}{2}}$$

Mr. E. Roscoe: Measurement of loop impedance, in accordance with the requirements of the 13th Edition of the Wiring Regulations, has provoked much thought on the design of instruments for carrying out the work, and on the associated problems of testing. There are certain facts which should be borne in mind in designing any such instruments, namely

(*a*) The tests will be carried out by installation inspectors or electricians.
(*b*) The instrument must be easily transportable and simple to operate.
(*c*) It must give a clear indication, preferably without calculation.
(*d*) Testing time must be kept to a minimum.

With these requirements, a set has been designed which tests the actual path of the fault current, using the phase conductor and applying a fault of limited current for a period not exceeding $1\frac{1}{2}$ cycles, and measuring the fault current during that period. A series of resistors are joined in turn between phase and earth, starting with the highest, with two circuit-breakers in series. The operating coils of the circuit-breakers are connected between phase and neutral. A multi-range tapping switch, marked in different fuse ratings, is set to the desired fuse rating. The test-button is pressed, applying a fault, which immediately trips the circuit-breakers. If the circuit will permit three times the current of the fuse rating to flow, a cold-cathode tube becomes illuminated, indicating that a fuse of that rating would operate and protect the circuit. This method of testing includes the supply-transformer impedance, and checks that the kVA rating is capable of supplying the fault current to operate the fuse.

In the author's equipment, has the 10 volts at 3 amp any special significance, or is it the limit of the physical capacity of the operator to turn the generator?

Mr. W. T. J. Atkins: The claim that what are called 'reversed d.c.' instruments measure resistance only and ignore reactance is false. The voltage applied to the test object is a square wave of variable frequency, and if there is inductance in the load the current will lag behind the voltage and its waveform will be distorted. The ohmmeter response will not even correspond to impedance, and the device of current chopping makes matters worse. However, in the applications for which the instrument is intended and where little inductance exists, there is no doubt that the effective elimination of all interference is of greater practical importance than technical accuracy of resistance measurement.

Mr. R. E. Jennings: Basically, I think that the manufacturer of such equipments should consider the safety of the equipment in use, its simplicity in operation, portability, cost, and rating. There has been much discussion about the correct current which should be passed through a test-piece, but no one has mentioned the protective multiple-earth systems: I believe that there is a specification to the effect that 10 amp should be passed through a $\frac{1}{2}$-ohm impedance or resistance for 5 min. With these points in mind we have manufactured an instrument and have decided on 10 amp as being a reasonable value for the current through a 1-ohm impedance. The author deals mainly with the accuracy of the equipment, but I believe that all the points I have mentioned should be considered in presenting a piece of equipment for engineers to use.

I have been associated with the development of the particular method referred to in Fig. 5, and in Table 1 the author shows values of R/R_p from 0·5 to 1·0. In fact, the circuit with which I am familiar gives $R/R_p = 0{\cdot}07$, so the errors which the author quotes can be rather misleading.

Secondly, I should like to indicate how the bridge method can be used to give a correct indication irrespective of neutral voltages appearing. An expression is given for the current in the balance indicator G, the right-hand side of which shows the current due to the voltage in the earth-neutral loop, namely $cV_n/(d + fR_q - gR_q^2)$. If we assume that V_n is zero, the bridge is adjusted to balance and I_g is zero: therefore $a - bR_q$ is zero. If we leave the bridge in the balanced condition and introduce a voltage V_n, there will be a certain current flow in the galvanometer, given by the expression above, but this current flow is independent of the phase angle of the neutral voltage. Thus, if the voltage on the test instrument is reversed, there will be the same indication of current in the balance indicator. This presents a new way of balancing the bridge.

If a high neutral voltage is present, zero current will not be obtained on balancing, but a current readable on the meter. If an attempt is made to find the position on the potentiometer which gives equal current for forward and reverse connections on the test voltage, the true point of balance which will satisfy the conditions will be found. The true resistance of the earth-neutral loop will be indicated immediately, irrespective of the existing neutral voltage.

Mr. H. S. Petch: Any test which involves measurement of current in the neutral of a 3-phase medium-voltage system must recognize the fact that considerable harmonic currents will usually be present, and appropriate ammeters must therefore be used. Moreover, the growing use of transformerless television receivers is giving rise to an increasing amount of direct current in the neutral conductor.

Mr. A. J. Baggott (*communicated*): The author's instrument has a most useful feature in that it requires no power supply in order to make a measurement. This facility can be of great benefit, particularly where large housing estates or blocks of flats have to be inspected before supplies are available. However, it has the great demerit that it measures resistance and not impedance.

The variation of the neutral-earth voltage has been rather over-emphasized. Clearly, networks exist where conditions are as described in the paper, but where networks are reasonably substantial the variations of the neutral-earth voltage over the short time required to make a measurement are insufficient to

cause any inaccuracy, provided that the instrument in use is capable of accommodating any such voltage irrespective of its phase or amplitude. It is agreed that instrument D falls short in this respect, and since it takes the mean of forward and reverse readings, it cannot give reasonable accuracy. It was to remedy this defect that, in 1950, the instrument described in Reference 2 was designed to satisfy the 12th Edition of the Wiring Regulations and has now been in use for some 6 years.

The idea originated by Mr. Roscoe is most realistic and can give the answer to the question whether a circuit can or cannot be protected by a fuse. The application of repetitive and controlled short-circuits can be applied with a simple electronic device which will give the impedance at the same time, and it is thought that an instrument of this type, having none of the mechanical features of the Roscoe instrument, but furthering his idea, will provide a real solution to the problem.

Commander H. J. P. Crousaz (*communicated*): The author omits any reference to the need for high current in such earth-continuity tests in order to establish the capabilities of the conductor in carrying sufficient current to actuate fuses or circuit-breakers. It is not impossible for a corroded or weak earth-continuity conductor to fail at a load which is less than that required to operate the circuit-breakers, thus rendering the equipment concerned dangerous to operators.

NORTH-WESTERN CENTRE, AT MANCHESTER, 8TH JANUARY, 1957

Dr. J. M. Cowan: The author explains that the square-wave a.c. hand tester overcomes some of the failings of the current-injection tester; but since the circuit whose resistance is measured is not the fault loop, the square-wave tester suffers from the major failing of the current-injection tester recommended in the 13th Edition of the Wiring Regulations. Where a low-voltage supply is provided from a system using protective multiple earthing and, as a result, the neutral and earth terminals on consumers' premises are connected together, both square-wave and current-injection testers used in the manner recommended in the 13th Edition would indicate zero impedance, and no simple modification to the testing procedure would allow the fault-loop impedance to be measured. There appears to be no point, therefore, in discussing the technical merits of the square-wave tester when used on low-voltage supply circuits or in comparing this type of tester with those of the current-injection type.

There is a vital need for an instrument which will indicate that a fuse will blow under fault conditions in accordance with Section 406 of the 13th Edition, and it is essential that the instrument should be applicable to cable systems and overhead-line systems with either protective multiple earthing or an aerial earth-wire. Such an instrument is available, and tests which have been carried out suggest that it is suitable for use on low-voltage supply circuits; it is hoped that early agreement on this point will be reached by engineers in the supply industry, so that adequate testing of low-voltage circuits may be achieved.

Mr. E. Roscoe: It is impossible to separate the discussion on the design of the author's instrument from the purpose for which it was made and the conditions under which it will be used. Regulations 406 and 507 of the 13th Edition lay down, respectively, the minimum earth-fault current in relation to the fuse-rating and the method of testing it. It is surprising that such an important regulation has been so long delayed, but it is welcomed, for it leads to greater safety. The method shown in the Regulations for carrying out this test is not satisfactory under certain conditions, and, in any case, it is undesirable to use the neutral conductor and assume similar results when using the neutral as a substitute for the phase. It is suggested that it is sufficient to state that the value of the earth-fault current should be measured without indicating the precise method of doing so.

The author's instrument is designed to generate a maximum of 3 amp at 10 volts, and he recommends a low-high-low current test in order to check whether there is an insulating film caused by oxidization of metals in the circuit of the earth fault. This is necessary only because of the low voltage applied, whereas the voltage under fault conditions would be that of the mains voltage—approximately 240 volts. The test for oxidization (causing the insulating film) is of academic interest only, and is one that electricians cannot afford time to investigate. It would be necessary to measure the voltage as well as the impedance, since it cannot be assumed to be 240 volts under present conditions. I have designed an instrument which applies a fault of limited current and indicates, by means of a cold-cathode tube, whether a fuse of a given current rating will operate under fault conditions.

Mr. W. McDermott: The organization with which I am associated has carried out loop tests since the 12th Edition first introduced impedance tests; but to use the loop test solely to obtain impedance is rather cumbersome. This introduction of impedance followed E.R.A. Report V/T111 on the impedance of steel conduit, which showed that at about 25 amp the impedance of conduit reached a peak of possibly five times its resistance, but that measurements of impedance could not be expected to give satisfactory indication of the quality of conduit joints. But conduit impedance is only part of the whole circuit impedance, and 30 yd of $\frac{5}{8}$ in diameter conduit has a resistance of only 0·1 ohm.

The Regulations compromised and called for a current $1\frac{1}{2}$ times the overload setting with a maximum of 25 amp. Designers of loop testers found it difficult to produce an instrument for this current which could be conveniently carried by an inspector, together with other equipment.

The author dismisses impedance as unimportant; in using a reversed d.c. instrument there is no fundamental difference from any other d.c. method. Three instruments were used with different ranges. Can we assume that the differences in results are observational errors, for in Test No. 14, Table 3, instrument C reads 25% lower than instrument A on direct connection, and 7% higher with 100 ohms in series?

I have carried out some tests with different instruments

Table A

Test	Loop-meter (volt-ammeter)	Loop-meter (volt-ammeter, variable current)			Loop-meter (bridge)	D.C. (ohmmeter)	Reversed d.c. hand generator	Continuity hand generator	Neutral to earth voltage
1	0·901	0·833	0·823	0·78	0·905	0·798	0·935	3·0	0·3
2	0·743	0·675	0·62	0·60	0·70	0·435	0·635	4·0	0·5
3	0·825	0·78	0·88	0·70	0·88	1·2	2*	4·5	0·9
4	1·1	1·04	0·998	1·03	1·18	1·1	1·1	6·0	1·9

* High value at small current traced to earth contact on aluminium finish-box.

measuring the same loops, shown in Table A. The conclusion one arrives at is that a reversed d.c. type of instrument does not pass sufficient current; furthermore, it has no advantage over a battery type, except that it is unaffected by stray direct currents—not usually a problem. The author has certainly shown the unreliability of loop testers, and there is sufficient evidence to call for consideration of the modification of Regulation 507.

Mr. F. Mather: The 13th Edition of the Wiring Regulations rightly emphasizes the importance of matching protective-gear settings to earth-fault loop impedance. The methods of testing to achieve this have been much discussed, and it remains to view the various factors in proper perspective. It is likely that electrical contractors will be mainly concerned with earth-continuity circuits within premises, in which case simple and inexpensive test equipment will serve their purpose.

It seems desirable that loop tests involving the public supply system should be made by, or in conjunction with, the supply authority, since proper appraisal of the test results involves knowledge of the mains system and the neutral earthing conditions. This applies particularly to rural areas, where, in general, the need for loop impedance tests is far greater than in towns, where a network of cable sheaths forms an effective return path for earth-fault current.

If the supply authorities' inspectors are to carry out large numbers of loop-impedance tests, the difficulty of transporting test equipment is one which cannot be ignored. From the supply authorities' point of view the phase/earth fault-throwing type of test set has advantages, because it is readily portable, tells immediately whether the proposed fuse size is suitable and can be arranged to measure leakage current—thereby probably rendering unnecessary other instruments which an inspector normally has to carry. It also takes account of such factors as protective-multiple-earthed systems, small supply transformers with appreciable voltage regulation and static balancers in the supply lines. In a percentage of cases where the test shows that a fuse, large enough to suit the load conditions, will not blow on earth fault, further investigation is necessary and the instrument described by the author is of value in obtaining the quantitative information then needed.

SOUTH-WEST SCOTLAND SUB-CENTRE, AT GLASGOW, 6TH MARCH, 1957

Mr. C. H. Smith: The importance of a loop test was first brought to my notice many years ago when a workman using a portable tool in damp surroundings received a fatal shock. The bonding of the consumer's installation proved very good, but the supply was taken from a pole-mounted transformer about ¼ mile away and the supply regulations at that time did not permit of bonding direct to the neutral. The resistance between the consumer's and the supply earth-plates proved to be 11 ohms. Investigation also revealed another earth connection, made to a buried lead pipe carrying running water, where the resistance to earth exceeded 20 ohms.

My experience of the current-injection method of testing is that the majority of results are reasonably accurate. I checked a circuit recently, and the loop measured by the current-injection method gave a resistance of 0·93 ohm, while a careful check of the separate resistances of the loop gave 0·99 ohm. It should not therefore be assumed that all the results are in error to the extent suggested in the paper. Furthermore, the use of the neutral (instead of the line) conductor would tend to make the resistance measured by this path higher than it really is, and the cases illustrated in the paper show errors in the current-injection method to be on the high side. This is considered an advantage on the principle that any failure should be a failure to safety. Furthermore, experience indicates that the majority of tests give either very good or very bad results, and of 146 tests made recently, 132 gave resistances twice as low as the maximum permitted by the Regulations, and, of these, many were only one-tenth of this. Equally, the bad cases were quite definite, and only nine of those tested were just a little above the permitted maximum. Such cases were always regarded with suspicion and were rechecked, irrespective of the method of testing.

While I agree that accuracy is very desirable, it should not be forgotten that testing is done in the field, where conditions are very different from the laboratory. Variations in the resistance can be obtained by merely increasing or decreasing the pressure applied on the test spike. Reading the instrument in awkward positions or dark corners involves uncertainties, and it is essential to allow a margin in all cases to cover such contingencies.

If accuracy were the only problem involved, the reversed d.c. instrument would undoubtedly be better, but it suffers from a serious drawback, i.e. it passes a very low current. A heavy current appears to be essential in carrying out these tests, and thus I believe that the current-injection method has an overall advantage.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Dr. G. F. Tagg (*in reply*): Several speakers have suggested that the voltage drop on the neutral remains constant for a sufficiently long time to enable a measurement to be made. This was not the case with the loops which I measured, the results of which measurements are given in the paper. The low speed of the recorder chart in Fig. 1 may be rather misleading in this respect. It has also been suggested that measurements should have been made when the earth-neutral voltage was zero. I thought the same at the time I made the tests, but after staying up all night on several occasions waiting for a time when this condition would exist, I found that at no time during the whole day was the earth-neutral voltage zero. I doubt whether this was a peculiarity of the particular loop in question.

A number of remarks have been made about accuracy, and it has been suggested that a high degree of accuracy is unnecessary. I do not think that anyone would have any confidence in a method of measurement which is known to be liable to considerable unknown errors. This is of particular importance in the borderline case, where errors might result in a good installation being condemned or a bad installation accepted.

The question of impedance or resistance has been raised several times. I am suggesting, not that there is no inductance, but that in the majority of cases—bearing in mind the whole loop—the inductance is not sufficiently high to make the impedance differ appreciably from the resistance. It may be that in a factory installation with a long conduit run that the inductance is appreciable, but in such a case with a substation on the premises the whole loop will probably be metallic, and the impedance or resistance will be very low. The reversed-d.c. instruments measure resistance and disregard reactance, and I would emphasize again that there is no phase displacement of the current if the circuit is inductive, since the circuit is completely broken twice in every cycle and at these breaks the current is forced to zero. If the inductance is very high it can produce distortion of the current wave, and this can cause a small error, but the inductance does have to reach a value much

higher than those encountered in practice for this to be the case. This matter has been thoroughly investigated both theoretically and experimentally.

I agree that the use of the neutral conductor is regrettable, and the probability of neutral faults which may or may not be in at the time of test only makes it more so. This is possibly a point outside the scope of the paper, for it suggests that the Regulation itself requires reconsideration. I do not think, however, that anyone would doubt the necessity for some test to ensure that a circuit is safe in the event of a fault. Fault resistance also plays a part, but in considerations such as those in the paper it is possible to deal only with the case when this is zero. It is obvious that with high fault resistance, no fuse will blow even if the loop impedance is zero.

The various instruments used in the tests were tried out on artificial circuits containing resistance only, and as nothing significant resulted from this there was no point in including these results in the paper itself. It is suggested that the errors given in Table 1 could have been presented in the form of curves, but so many variables are involved that it was not possible to present the information in such a compact form, nor did time permit the labour involved in making the necessary calculations.

A test with a pure d.c. supply may give a satisfactory result if both polarities of testing voltage are used, but this suggestion introduces another point which has to be considered. To obtain a current of, say, 20 amp at a reasonable voltage, say 20 volts, means a power of 400 watts, and whether an a.c. test with a transformer or a d.c. test with a battery is used, the weight of the testing equipment may be considerable and this is an additional weight for the contractor or installation inspector to carry. If the loop contains earth electrodes, the reversed-d.c. instruments have an advantage in that they eliminate the effects of stray currents and electrolysis.

Another point is whether the magnitude or the phase angle is the more important, and which one varies most. I do not think this matters: both are important and both seem to vary continuously. The low-high current test is useful in finding faulty joints, and I would point out that it is not safe to assume that the system voltage will always break down any oxide film which is likely to become worse with time.

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Aug. 1956

CHOICE OF INSULATION AND SURGE PROTECTION OF OVERHEAD TRANSMISSION LINES OF 33 kV AND ABOVE

By A. MORRIS THOMAS, B.Sc., F.Inst.P., Member, and D. F. OAKESHOTT, B.Sc., Associate Member.

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SUMMARY

The paper is essentially a short critical résumé of the factors which, in general, determine the security of high-voltage a.c. overhead-line transmission systems with, in addition, a description of methods which provide a logical basis for the efficient selection of insulation levels.

Transient over-voltages are the main source of danger to overhead-line insulation; they may be of internal origin, but lightning strokes are the major hazard, particularly in oversea countries where lightning is prevalent. Lightning phenomena are therefore considered; statistical data on lightning currents, stroke frequency and other variables are included. The problem of shielding by earth wires and the importance in this connection of tower footing resistance are discussed.

A description of the characteristics of line insulation is given; this includes data on power-frequency and impulse tests, flashover voltages, atmospheric influences, deterioration, use of wood poles, and other related matters.

The selection of insulation levels involves careful consideration of the foregoing factors with, in addition, a means of estimating line reliability or probable outage frequency. Two methods which have been developed for predicting line performance under lightning conditions are described and compared, and their application is illustrated by numerical examples.

(1) INTRODUCTION

The purpose of the paper is to give guidance to the selection of insulation and surge protection for 3-phase high-voltage overhead-line transmission systems, with special reference to countries oversea where lightning is prevalent. The restriction to system voltages of 33 kV and above is deliberate; at lower voltages the problem is more complex although admittedly the same in principle. The insulation to be considered comprises suspension-, tension-, pin- and post-insulators made of porcelain or toughened glass, and air clearances, including protective gaps.

A major source of danger to the continuity of an overhead-line system is breakdown of the system insulation by the over-voltage surge which is produced when a lightning stroke terminates on a phase conductor, earth wire or tower. The insulation concerned may be that of the line itself or of the apparatus in installations to which it is directly connected and which, for this reason, are called 'exposed installations'.

Considerable progress has been made by the International Electrotechnical Commission towards the establishment of insulation co-ordination standards for exposed installations.[1] These I.E.C. standards consist of a series of values of system voltages and the corresponding standard insulation levels expressed in terms of impulse-withstand (1/50 microsec wave) and power-frequency-withstand voltages.

The choice of insulation for the line itself, when lightning is to be expected, requires a different method of approach and no standards have so far been proposed. The I.E.C. standard power-frequency insulation level suffices to ensure that the insulation will not break down as a result of internal over-voltages, and is therefore a guide to the minimum line-insulation requirement applicable if the lightning hazard were non-existent.

A simple line flashover caused by a transient over-voltage due to lightning is usually, in itself, innocuous and accepted as an unavoidable occurrence, but it is likely to be followed by a power-frequency arc which may not only damage the line insulation but also cause an outage or interruption of supply owing to the operation of protective gear by the earth-fault current.

The methods commonly used to counteract the effects of lightning on lines are (*a*) earth-wire shielding to reduce the chance of a direct stroke to a phase conductor; (*b*) arcing fittings to reduce the chance of damage to an insulator or conductor by a 'follow' arc, and (*c*) provision of sufficient insulation to reduce outage frequency to a tolerable level. A more recent development is the use of automatic high-speed reclosing switchgear to reduce outages due to line flashovers.

The considerations involved in fixing a permissible outage frequency are mainly economic and depend on a comparison of the benefits resulting from a reduction of outages with the cost of providing more insulation. Sufficient data are now available to enable the lightning performance of a given overhead line to be approximately predetermined or, alternatively, to enable the insulation required to give a prescribed performance to be approximately estimated.

Some degree of personal judgment will still remain in selecting higher insulation levels for high crossings, for regions of severe atmospheric pollution and for parts of the line where access is difficult.

(2) LIGHTNING

(2.1) The Lightning Stroke

Lightning denotes the electrical discharge phenomena which are essentially associated with thunderstorms. A lightning stroke[2, 3] is a very high surge of current which may pass between earth and a thundercloud, or between two thunderclouds, and is the cause of the intensely luminous lightning flash. Only strokes to earth are of interest and importance in overhead-line transmission.

The complete lightning stroke consists essentially of at least two components: the leader and the return stroke. The tip of the leader travels to earth in a series of steps, each about 10 m long, at time intervals of about 50 microsec, so that it has an average velocity of 200 km/s, and during the greater portion of its path its direction is determined by the space-charge field beneath the cloud and not at all by soil characteristics or surface conditions. The intensity of the field at the ground increases as the tip of the leader approaches, until it becomes sufficient to start a discharge at some local surface irregularity. An upward

This is an 'integrating' paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

The paper is based on Report Ref. O/T14 of the British Electrical and Allied Industries Research Association.

Mr. Thomas is with the British Electrical and Allied Industries Research Association.
Mr. Oakeshott is at the Central Electricity Authority Laboratories.

streamer develops from this point and meets the downcoming leader; a conducting channel from cloud to ground is thus established, and a heavy current pulse of the order of 10–100 kA passes. This is the highly luminous return stroke; its initial velocity of propagation is of the order of one-tenth the velocity of light.

One or more succeeding leader strokes, each followed by a return stroke, may occur, charge being fed to the top of the original main discharge channel by breakdown from other charge centres. On the average, not more than one or two strokes follow the first, although a maximum of forty has been observed. The time interval between the components of multiple strokes is usually about $\frac{1}{20}$ to $\frac{1}{10}$ sec with a maximum of about $\frac{1}{2}$ sec. Succeeding leader strokes follow the main channel and do not have the stepped characteristic shown by the first.

Individual strokes may be accompanied by long-duration low-amplitude current 'tails', which, in multiple strokes, may take the form of maintained current discharge. In general, the long-term low-amplitude component of the lightning current dissipates a much larger charge than the impulsive high-current component; it is usually the cause of the incendiary effects and is sometimes referred to as 'hot lightning', whilst the impulsive part, which has explosive effects, is called 'cold lightning'.

(2.2) Effect of Lightning Strokes on Overhead Transmission Lines

When an overhead-line system is struck by lightning, the stroke may terminate on either a phase conductor, a tower, or the earth wire if one is provided. The amplitude of the initial voltage surge produced at the point struck will be equal to the product of the amplitude of the lightning current and the effective impedance presented by the path or paths to earth. If lightning strikes a phase conductor or earth wire, the effective impedance to earth, taking into account that the lightning current divides between the two directions open to it, is about 250 ohms, this value being about half the surge impedance of a line conductor. The surge impedance of the lightning arc channel has been given as approximately 5 000 ohms, but since the velocity of the return stroke is one-tenth that of light it is considered preferable to regard the stroke channel as a constant-current source rather than a surge impedance.[4,5,6]

If lightning strikes direct to a tower, the impedance presented is that due to the inductance of the tower in series with the tower footing resistance. For a lattice tower the inductance is about 10 μH per 100 ft; for a rate of rise of lightning current of 10 kA/microsec, the voltage drop in the tower will be 1 kV/ft. The commonly accepted rule is to ignore the tower inductance and to calculate the amplitude of the lightning surge on the tower as the product of the current peak and the tower footing resistance. Operational experience has shown this to be satisfactory when the tower footing resistance exceeds about 10 ohms. Below this value, or for unusually tall towers, the effect of tower inductance becomes appreciable. With much higher tower footing resistances a portion of the lightning current is discharged along the conductors to the neighbouring towers. The voltage surge suffers reflection back to the original tower and tends to reduce the amplitude of the original surge, since it arrives back when the voltage on the tower is still increasing and is of opposite polarity.

To estimate the voltage rise at the tower caused by a lightning stroke to the earth wire at mid-span, the wire can be regarded merely as an extension of the lightning channel, the discharge passing simultaneously through the two neighbouring towers in parallel so that the amplitude of the surge at the tower is half that produced if a tower is struck directly.

The initial effect of a lightning stroke to a phase conductor is the same as that to an earth wire except that the insulators at neighbouring towers flash over before the discharge passes through the tower to earth.

The disturbance on the line is propagated in both directions with the velocity of light. The surge which reaches the neighbouring insulation is of steep wavefront, and, owing to the breakdown time lag of insulators, a part of the original surge voltage passes the insulators before they flash over, and the next pair of insulators may therefore also flash over. Thus a surge, in travelling along the line from the point struck, has its amplitude reduced to a value below the insulation level of the line and arrives, attenuated, at the station. A surge during its travel is attenuated not only by insulation flashover but also by the effects of line resistance, leakage, inductance, capacitance, skin effect, earth resistance, propinquity of other conductors and corona.

The result is that if the line is struck at a point remote from a station, the lightning surge arrives at the station with an amplitude somewhat less than that corresponding to the insulation level of the line and with reduced steepness of wavefront. On the other hand, if lightning strikes the line near a station, the amplitude of the incoming surge may greatly exceed the insulation level of the line and may have a very short wavefront and a chopped tail; a wave of this nature will impose particularly severe stresses on the over-voltage protective equipment.

If a line is connected to one or more lines of equal or similar surge impedance, the amplitude of a surge propagated along individual lines is much less than that of the original; hence interconnection is very beneficial.

The amplitude of the voltage surge produced at a tower either by direct lightning stroke or by a stroke to the earth wire at mid-span is, as already stated, approximately equal to the product of the lightning current peak and the tower footing resistance. This may amount to a million volts or more, and is therefore likely to produce a discharge (over the insulators from the tower to a phase conductor) known as 'back-flashover'. Usually only that phase conductor which presents the greatest instantaneous voltage of polarity opposite to that of the surge will be involved, but multiphase flashovers are not uncommon, the proportion decreasing with increasing system voltage.[18] The voltage surge on the phase conductor so produced will then travel away in both directions along the line and arrive finally at a station after undergoing attenuation as in the case of the surge due to a direct stroke.

Apart from a shielding failure or mid-span flashover from the earth wire, both of which are relatively infrequent, back-flashovers are the only source of insecurity that can arise from lightning strokes to a system adequately shielded by one or more earth wires.

Surges may be induced on overhead lines by lightning strokes which terminate near but not on the line; such so-called indirect lightning strokes are now known to be of no practical importance on systems operating at about 33 kV and above.[7]

(2.3) Isoceraunic Levels

The extent to which the design and performance of an overhead-line system will be influenced by lightning phenomena depends on the frequency of outages caused by lightning strokes to the system during a given time, and this in turn is related to the frequency of lightning strokes to earth in the area covered by the system. It is accepted practice to relate the lightning frequency in any region to the isoceraunic level, the definition of which is the number of days in a year on which thunder is heard in that region. The isoceraunic level is not an accurate measure of the frequency of lightning strokes to earth, but so far no better reference magnitude has been suggested.

Tropical storms are regarded as being very severe but, in fact,

the ratio of cloud–earth to cloud–cloud strokes is appreciably less than that found in temperate zones. A rough rule is that, in temperate zones, the number of cloud–earth strokes per square mile per year is half the isoceraunic level for the area concerned, and in the tropics it is one-third.[2] The cloud–earth stroke frequency probably increases with height of the ground. High earthed metal projections are known to be struck more frequently than the surrounding flat ground.

A world map showing the distribution of frequency of lightning strokes to earth per square mile per year is reproduced in Fig. 1.[2] Over regions for which sufficient observational data are available a finer analysis would, of course, be possible and would probably reveal local areas with higher frequencies than the averages indicated.

(2.4) Frequency of Strokes to Transmission Lines

A Committee of the American Institute of Electrical Engineers[8] concluded from an analysis of available data that the number of strokes to a given length of line is independent of the line type (system voltage) and directly proportional to the isoceraunic level of the terrain; that, for an isoceraunic level of 30, one stroke per mile of line per year may be expected, and that the number of strokes which terminate at towers is equal to the number termi-

(c) Line with two earth wires:

$$A_3 = 3\cdot 2h_t^2\pi + (l - 3h_t)(b_0 + 3h_0) \quad . \quad . \quad . \quad (3)$$

In these expressions

A_1, A_2, A_3 = Area 'covered' per span.
h_t = Height of tower.
h_0 = Average height of earth wire above ground.
h_p = Average height of phase wires above ground.
b_0 = Horizontal distance between earth wires.
b_p = Horizontal distance between outermost phase wires.
l = Span length.

If the dimensions are in feet,

$$N = \frac{\alpha(IL)A \times 10^{-2}}{l} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where N = Number of strokes-to-line per 100 miles of line per year.
(IL) = Isoceraunic level.
A = Appropriate area 'covered'.
α = 1 for temperate zones and $\frac{2}{3}$ for the tropics.

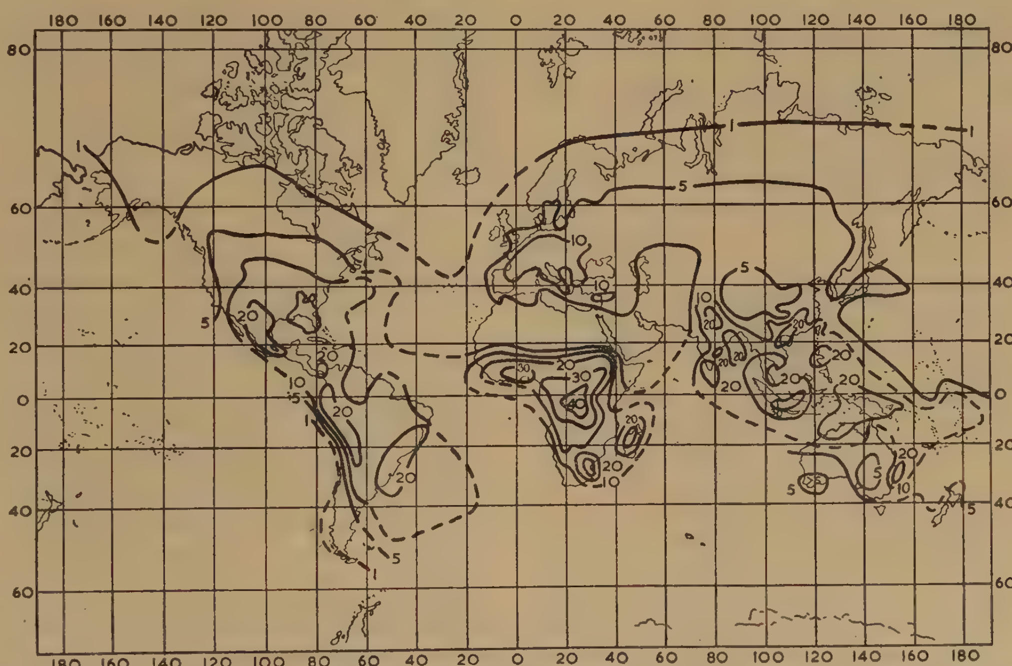

Fig. 1.—World map showing estimated number of lightning flashes to earth per square mile per year. (C. E. P. Brooks, 1950.)

nating at mid-span. These data refer to lines provided with a single earth wire positioned to give shielding failures not exceeding 0·1%.

The E.R.A. method[9] for estimating the probable stroke-to-line frequency is based on a calculation of the area covered by the line, using formulae which are derived from a consideration of modern theory of lightning discharges. Three formulae corresponding to different types of transmission line are presented as follows:

(a) Line without earth wire:

$$A_1 = 4h_t^2\pi + (l - 4h_t)(b_p + 2h_p) \quad . \quad . \quad . \quad (1)$$

(b) Line with one earth wire:

$$A_2 = 3\cdot 6h_t^2\pi + (l - 3\cdot 2h_t)3h_0 \quad . \quad . \quad . \quad . \quad (2)$$

In the formulae for A, the areas 'covered' by the tower and conductors are the first and second terms on the right-hand side respectively, so that the quotient of these magnitudes gives the ratio strokes-to-tower/strokes-to-mid-span. Mid-span here denotes any point in that part of the span which falls outside the area 'covered' by the towers. In the report in Reference 8 mid-span denotes any point in the central half of the span and strokes to towers include strokes terminating on the quarter-spans adjacent to towers.

In the absence of more accurate knowledge it is usual to assume that the number of strokes to earth is proportional to the isoceraunic level. The suggestion has been made, however, that this number is proportional to the isoceraunic level raised to a power somewhat greater than unity.[10]

(2.5) Lightning Currents, Voltages and Waveforms

The waveform of a lightning current surge, such as is carried through a lightning conductor when struck, is very roughly of double exponential form; the wavefront time falls within the range of 2–10 microsec and the tails extent to 60 microsec; on the average the waveshape approximates to a 5/25 microsec wave.

For the predetermination of line performance (Section 7) the American I.E.E. Committee[8] takes a 4/40 microsec wave as representative of a lightning current surge; for the same purpose the E.R.A.[9] adopts a wavefront time of 6 microsec, the actual duration of wavefront, according to the I.E.C. definition, being 3·8 microsec.

The cumulative frequency curve of lightning currents of 5 kA and over is given in Fig. 2.[11] About 80% of lightning strokes to transmission lines are of negative polarity, i.e. a negative charge is lowered to earth.

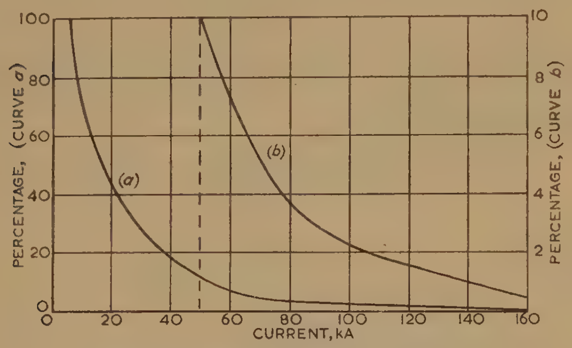

Fig. 2.—Currents in lightning strokes.

Ordinates give percentage of strokes having currents exceeding abscissa value, neglecting those below 5 kA.

The maximum value of lightning current to be expected is probably about 160 kA and the maximum rate of rise of wavefront of a lightning current surge through a transmission tower is about 65 kA/microsec.[5]

The surge voltage impressed on a conductor by a direct stroke has roughly the same waveshape as the lightning current it carries, but a back-flashover gives a surge of steeper wavefront.

(3) SHIELDING BY EARTH WIRES

Earth wires are conductors, suspended above the phase conductors, which are earthed by bonding to the tops of the towers and to station earths. An earth wire tends to attract to itself lightning strokes which would otherwise strike the phase conductors. Since a phase conductor is actually or virtually insulated from earth, at any rate with respect to lightning surges, it does not attract lightning strokes so effectively as an earth wire, so that the number of lightning strokes to the line as a whole is increased by the presence of the earth wire, although only a very few strokes terminate on the phase conductors under these conditions.

The protection provided by earth wires is essentially dependent on tower footing resistances, which must be as low as possible. Special measures (see Section 4) may have to be used where low tower footing resistances are unobtainable by conventional methods owing to the nature of the ground; alternatively, it may be better economically and technically to do without earth-wire protection and to raise the insulation level of the line by using longer insulator strings or wood poles, or to install protective spark-gaps (protector tubes) in parallel with the insulators, although such gaps are not likely to be applicable to very-high-voltage lines.

Experience suggests that if the protected zone is taken as the area subtended at the earth wire by lines inclined downwards at approximately 30° to the vertical, the probability of a shielding failure is sufficiently low.

Apart from lightning protection, an earth wire has the beneficial effect of reducing the wavefront steepness and the amplitude of surges on the phase conductors, by electrostatic and electromagnetic coupling.

On single-circuit lines arranged horizontally adequate shielding can be provided only by using two earth wires. This is recommended in regions where lightning is particularly severe and for the first mile from the station. In Great Britain, where lightning is not of great severity, one earth wire for double-circuit lines is used.

Shielding on double-circuit lines can be just as effective as on single-circuit (triangular spacing) lines, provided that the earth wire is placed sufficiently high.

(4) TOWER FOOTING RESISTANCES

The importance of providing low tower footing resistance in order to reduce the severity of lightning over-voltages when a tower or earth wire is struck by lightning has already been emphasized.

When, owing to the electrical resistivity of the soil, the tower footing alone is inadequate, the footing resistance is reduced by connecting the tower base to rods driven into the ground, or to conductors buried in the ground. Copper rods of 8–12 ft in length driven into the soil provide an economic form of earth electrode. The accepted formula for the resistance, R, of a rod in soil of resistivity ρ is

$$R = [3{\cdot}7\rho \log_{10}(4l/d)]/l \text{ ohms}$$

where l is the length and d the diameter of the rod; if ρ is given in ohm-centimetres l must be given in centimetres; d must, of course, be given in the same units as l. Where several rods are required, their separation should be at least equal to their length.

The resistance of an earth electrode is greatly increased by passage of a heavy current. Field tests have shown that for a sustained fault the current in a $\frac{5}{8}$in-diameter 12 ft rod should not exceed 150 amp in soil of resistivity 5 000 ohm-cm. An earth plate has a higher current-carrying capacity and has the advantage of a higher electrostatic capacity which tends to reduce the initial impedance for steep-fronted lightning surges; on the other hand, high installation cost may make the use of earth plates uneconomic.

When the conditions preclude the use of driven rods, e.g. when hard rocky soil is encountered, an earth connection can be obtained by burying conductors in relatively shallow trenches. A buried conducting wire is known as a counterpoise; the use of this method is increasing in countries where lightning conditions are very severe. The direction of the counterpoise wire is immaterial unless the resistivity is so high that the length of counterpoise required is equal to, or greater than, a span, in which case it is beneficial to run a continuous counterpoise parallel to the line and connected to every tower. For shorter lengths several wires are better than one long one, but the length of each wire should not be less than 250 ft. A continuous counterpoise increases the coupling coefficient between tower and phase conductor and thus tends to reduce the amplitudes of lightning over-voltages.

When the earthing device consists of a rod or plate the resistance to earth offered to an impulse voltage is usually taken to be the same as that determined by a portable ohmmeter. It is known,[12] however, that the effective resistance for the higher range of lightning discharge currents is appreciably lower than

the d.c. or low-frequency resistance, and for this reason it has been suggested that the earthing resistance might be based on a high-frequency or impulse measurement.

The impulse earth resistance of a counterpoise in a high-resistivity soil is its effective surge impedance; this parameter rises from zero to its maximum value in less than 1 microsec and then slowly decreases to the d.c. value.

The maximum values of resistance given by 1 000 ft of counterpoise wire disposed in various ways have been estimated to be of the following order:[13]

1 000 ft in one direction	150 ohms
2 × 500 ft in two opposite directions ..	75 ohms
4 × 250 ft in star formation	35 ohms

To derive the greatest benefit from low tower footing resistances, it is necessary that the overhead earth wire be earthed at every tower or pole; any measurement of the earth resistance must, of course, be made with the overhead earth wire disconnected.

(5) LINE INSULATION CHARACTERISTICS

(5.1) Impulse Voltage Tests

The waveform for impulse tests adopted by the I.E.C. and used extensively in Great Britain and on the Continent is the 1/50 microsec wave; impulses of both polarities are usually applied. In the United States a 1·5/40 microsec wave has been generally used as standard; this gives a slightly less severe condition, but the effect is insignificant compared with variations due to other causes. In fact, the 1·5/40 microsec wave lies just within the tolerance on the time-to-crest and time-to-half-value permitted by the British Specification for the 1/50 microsec wave.

In considering impulse flashover values account must be taken of the criterion of measurement; the so-called 50% value is that which causes flashover in one-half the number of applications on the average, say five times out of ten; analogously the 100% value and 0% or withstand values have obvious meanings.

The result of any test, or the specified test voltage applied, must be corrected to conform with standard atmospheric conditions. The accepted standards are: temperature 20° C, pressure 760 mm Hg, and absolute humidity 11 g/m³ (64% r.h. at 20° C). The appropriate correction factors are considered in Sections 5.2, 5.3 and 5.4. When tests are made in the presence of a water spray to simulate rain the air-density correction still applies.

In order to demonstrate the surge protection provided by insulators, rod-gaps, surge diverters, etc., it has become customary to draw a set of time-lag curves such as those shown in Fig. 3.[14] This procedure is convenient for illustrative purposes but the picture presented is over-simplified and, to some extent, gives a false impression of the precision obtainable.

(5.2) Effects of Temperature and Pressure

The flashover voltage, V, of insulators and rod-gaps (for both power-frequency and impulse waves) as a function of electrode spacing, s, agrees fairly closely with an expression of the form

$$V = ks^{\alpha}$$

where $\alpha = 0{\cdot}9$ (approx.).
k = A constant depending on the electrode system and type of voltage.

On the assumption that Paschen's law applies, V is proportional to $\delta^{0\cdot9}$, δ being the air density, but it may be questioned whether this is valid for insulators where corona occurs before flashover, and where the same relative field geometry is not strictly maintained because of the addition of units to an insulator string.

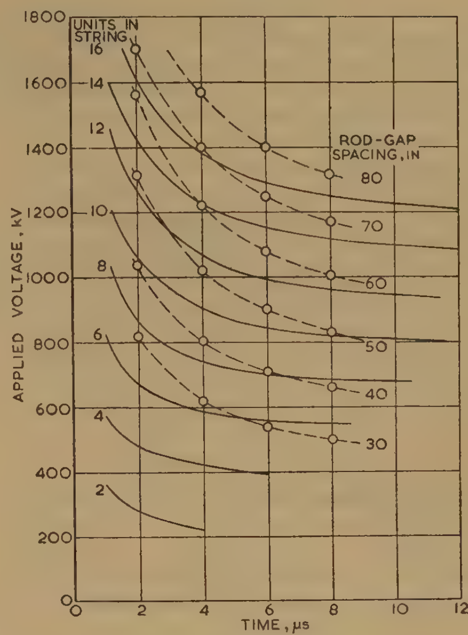

Fig. 3.—Time-lag curves of suspension-insulator strings (full lines) and of rod-gaps (broken lines).

Insulator strings had 10 in-diameter discs at 5 in spacing and were without arcing fittings. Impulse was 1/50 microsec wave, positive and negative.

However, for the range of normal atmospheric temperatures and pressures met with in testing and experimental work at any particular locality, direct proportionality of V and air density is usually assumed.

(5.3) Effect of Altitude

Both temperature and pressure decrease with altitude, the pressure decrease predominating, so that the air density relative to that at sea level also decreases.

The empirical atmosphere adopted by the International Civil Aviation Organization (I.C.A.O.) and known as the 'international

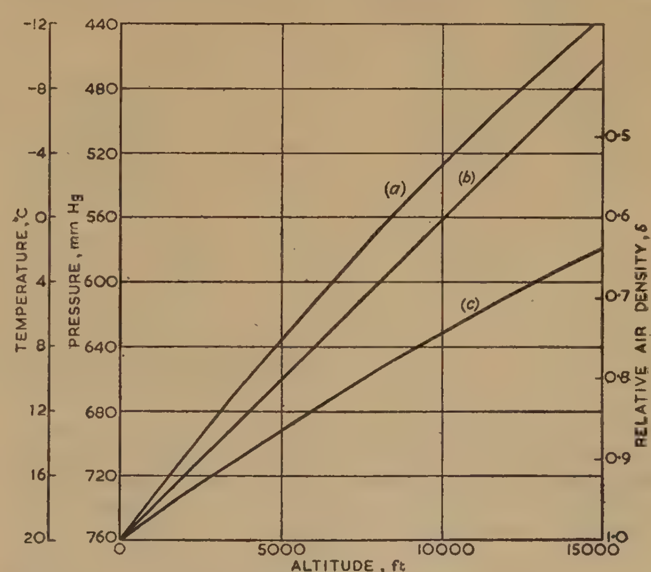

Fig. 4.—Pressure, temperature and relative air density as functions of altitude with respect to 20° C and 760 mm Hg at sea level.

(a) Pressure (I.C.A.O.).
(b) Temperature (I.C.A.O.).
(c) Relative air density (I.C.A.O.), δ.

standard atmosphere' is now accepted as giving the closest representation of atmospheric conditions found in various parts of the world.[16] The variations of pressure, temperature and relative air density with altitude are shown in Fig. 4; these curves correspond to the I.C.A.O. standard-atmosphere values corrected to a sea-level temperature of 20° C.

When the relative air density is adopted as the correction factor for altitude, the variation is approximately equivalent to an increase of 3·5% in flashover voltage for each 1 000 ft decrease of altitude. Experimental results of rather limited scope have recently been reported in the United States; they indicate that, on the average, the flashover voltage of insulators and air-gaps is approximately proportional to the 0·75th power of the air density,[15] and theoretical grounds for a 0·9th-power law have been given in Section 5.2. If the latter is accepted, the altitude correction factor is reduced to about 3%/1 000 ft.

(5.4) Effect of Humidity

Flashover voltages vary with the humidity of the air, and the variation is directly related to the concentration of water vapour in the air irrespective of temperature and pressure. Sets of correction factors to be used for impulse and power-frequency tests respectively (see Table 1) have been adopted as applying approximately to all designs. The possible error involved should be minimized by making tests under conditions of humidity as close as possible to the standard condition of 11 g water vapour per cubic metre of moist air, but such tests are inadmissible if the relative humidity exceeds 95%.

To avoid repeated references to tables and numerical calculations, nomograms for various forms of hygrometers have been prepared,[17] whereby the humidity correction factor can be obtained directly from the readings of the instruments with errors within ±1%.

(5.5) Effect of Atmospheric Pollution

Deposition of salt in coastal regions and of dirt from polluted air in industrial districts are important causes of failure of overhead-line insulation, particularly under conditions of high humidity. In areas where atmospheric pollution is severe it is customary to use insulators specially designed to mitigate the effects of surface contamination by the provision of longer creepage distances or by other means. An anti-fog insulator for use in Great Britain is designed to give a minimum creepage path of 1 in for each kilovolt between phases, but for the highest system voltages under the worst conditions even this value is inadequate and a longer creepage path per kilovolt is probably advisable with conventional insulators. Routine live-line washing is a useful means of combating insulation pollution if carried out regularly, but is rarely practicable. Surge diverters have been known to fail at normal service voltage in humid and polluted atmospheres owing to surface pollution which disturbed the normal voltage distribution.[18] Semi-conducting glaze may provide a means of maintaining a uniform potential-grading over the surfaces of insulators exposed to pollution, but the glaze available at present deteriorates when in contact with the electrolytes which almost invariably exist in the surface contaminant.

Long-rod (Langstab) porcelain insulators are finding increasing use oversea especially on very-high-voltage systems.[19] Single units up to a maximum length of 4 or 5 ft are manufactured. The claims that they are superior with respect to resistance to pollution and tendency to arc cascading have yet to be established.

Table 1

Humidity Correction Factors for Flashover Voltage of Insulators with or without Arcing Fittings Relating to the Standard Condition of 11 g/m³

(Relative humidity should not exceed 95%)

Absolute humidity			Correction factor	Absolute humidity			Correction factor
For impulse tests (1/50 microsec wave)		For power-frequency tests		For impulse tests (1/50 microsec wave)		For power-frequency tests	
Positive	Negative			Positive	Negative		
g/m³	g/m³	g/m³		g/m³	g/m³	g/m³	
—	—	1·4	1·12	11·0	11·0	11·0	1·00
—	—	2·2	1·11	12·0	12·2	11·8	0·99
1·0	—	3·0	1·10	13·0	13·5	12·7	0·98
2·0	1·2	3·8	1·09	14·1	14·7	13·6	0·97
3·0	2·3	4·6	1·08	15·2	16·0	14·5	0·96
4·0	3·3	5·3	1·07	16·4	17·3	15·4	0·95
4·9	4·4	6·1	1·06	17·7	18·7	16·4	0·94
5·9	5·4	6·9	1·05	19·0	20·2	17·3	0·93
6·8	6·5	7·7	1·04	20·4	21·9	18·4	0·92
7·8	7·5	8·5	1·03	22·0	23·8	19·5	0·91
8·8	8·6	9·3	1·02	23·7	—	20·8	0·90
9·9	9·8	10·2	1·01	—	—	22·0	0·89
11·0	11·0	11·0	1·00	—	—	23·2	0·88

The measured flashover voltage at a given absolute humidity is multiplied by the appropriate correction factor to obtain the flashover voltage at the standard humidity.

(5.6) Deterioration

In order to maintain the line insulation level, the early detection and removal of faulty insulators is very desirable. To this end, live-line testing may be carried out regularly. On the British

Grid, for example, faulty units are found in 0·01 to 0·1% of insulators so tested every year. The fault is usually due to a crack in the porcelain unit between cap and pin. Apart from this type of fault there is no evidence that insulators in service in clear atmospheres are subject to deterioration in insulation resistance, flashover or puncture voltage as a result of ageing. In polluted atmospheres, however, heavy encrustations of dirt are deposited on the surface of the insulator and may cause progressive deterioration.

(5.7) Comparison of Porcelain and Toughened-Glass Insulators

Whether porcelain or toughened-glass insulators give the better performance in service has yet to be established. At present there is no appreciable difference in cost. The flashover characteristics are similar, and although the electrical puncture strength of glass with impulse voltages is about three times higher than that of porcelain this property is not a decisive factor.

A toughened-glass insulator shatters completely when damaged mechanically, and such damage is therefore easily detectable without live-line testing; merely superficial damage which does not penetrate the toughened layer does not cause shattering and does not make the insulator unserviceable. This shattering effect, however, makes toughened-glass insulators attractive targets for rifle-shooting enthusiasts.

With porcelain insulators, hair-line cracks may render an insulator mechanically defective but may escape notice until failure occurs unless special tests are applied.

The temperature rise due to absorption of solar radiation is similar for clean glass and white porcelain but is higher for brown porcelain. No differences in humid or polluted atmospheres have been observed.

(5.8) Flashover Voltages of Insulators and Rod Gaps

Typical power-frequency flashover voltages of British and United States insulator strings without arcing fittings are given in Tables 2 and 3 for the dry and wet condition (cf. B.S. 137:

Table 2

TYPICAL POWER-FREQUENCY FLASHOVER VOLTAGES OF OVERHEAD-LINE INSULATOR STRINGS WITHOUT ARCING DEVICES (DRY CONDITION)

Temperature, 20° C; Pressure, 760 mm Hg

Number of units	Flashover voltage					
	For 10 in-diameter insulators spaced at				For 12 in-diameter insulators spaced at	
	5 in	5¼ in	5½ in	5¾ in	7 in	8¾ in
	kV, r.m.s.	kV, r.m.s.	kV, r.m.s.	kV, r.m.s.	kV, r.m.s.	kV, r.m.s.
2	135	141	145	—	160	180
4	235	245	250	270	300	340
6	330	346	350	385	436	496
8	420	437	450	490	560	640
10	510	524	548	590	668	768
12	590	604	638	685	760	880
14	670	682	720	770	838	978

1941). Power frequency means almost invariably 50 c/s in the United Kingdom and Europe generally and 60 c/s in the United States; this difference, however, has no significant effect on flashover voltages.

Fifty per cent impulse flashover voltages for similar strings are given in Table 4 for the dry condition (11 g water vapour per

Table 3

TYPICAL POWER-FREQUENCY FLASHOVER VOLTAGES OF OVERHEAD-LINE INSULATOR STRINGS WITHOUT ARCING FITTINGS (WET CONDITION)

Temperature, 20° C; Pressure, 760 mm Hg

Number of units	Flashover voltage					
	For 10 in-diameter insulators spaced at				For 12 in-diameter insulators spaced at	
	5 in	5¼ in	5½ in	5¾ in	7 in	8¾ in
	kV, r.m.s.	kV, r.m.s.	kV, r.m.s.	kV, r.m.s.	kV, r.m.s.	kV, r.m.s.
2	85	87	87	—	100	120
4	165	170	175	183	199	240
6	239	247	255	264	293	353
8	310	320	330	346	379	459
10	380	390	400	416	457	557
12	448	459	470	488	528	648
14	514	526	538	570	595	735

Table 4

TYPICAL 50% IMPULSE FLASHOVER VOLTAGES OF SUSPENSION INSULATOR STRINGS WITHOUT ARCING FITTINGS (DRY CONDITION, 11 G/M^3 WATER VAPOUR)

Temperature, 20° C; Pressure, 760 mm Hg

Number of units	Flashover voltage		
	For 10 in-diameter insulators spaced at		
	5 in	5½ in	5¾ in
	kV, peak	kV, peak	kV, peak
2	218	240	260
4	380	420	440
6	523	570	610
8	658	720	780
10	793	880	960
12	940	1 040	1 120
14	1 100	1 190	1 290
16	1 200	1 340	1 460
18	1 340	1 490	1 630
20	1 470	—	1 790

Values for 5 in spacing are N.P.L. results[14] obtained with 1/50 microsec wave, positive and negative.

Values for 5½ in spacing are manufacturers' data, obtained with 1/50 microsec wave, positive.

Values for 5¾ in spacing are United States data,[15] obtained with 1·5/40 microsec wave, positive and negative.

cubic metre). Time-lag curves for strings of the 10 in-diameter 5 in-spacing insulator units, together with similar curves for a number of rod-gap settings (remote earth), are given in Fig. 3.

The impulse flashover voltage of an insulator string is only slightly dependent on the polarity of the impulse, and this applies also to rod-gaps when remote from an extensive earthed surface.[14] With rod-gaps assembled according to a standard arrangement formerly adopted, the positive impulse flashover voltages were approximately 20% less than the negative. The curves for rod-gaps given in Fig. 3 are for a remote-earth arrangement (15 ft above floor level) and are intermediate between curves for positive and negative polarities obtained with the standard arrangement mentioned.

Anti-fog insulator strings give dry impulse flashover voltages of approximately the same values as ordinary insulator strings having the same minimum length of flashover path.

Typical power-frequency and impulse flashover voltages for

Table 5

TYPICAL FLASHOVER VOLTAGES OF PIN-INSULATORS SUITABLE FOR SYSTEM VOLTAGES OF 30–66 kV

Temperature, 20° C; Pressure, 760 mm Hg

System voltage	Total leakage distance	Flashover voltage			
		Power frequency		50% impulse	
		Dry	Wet	Positive	Negative
kV, r.m.s.	in	kV, r.m.s.	kV, r.m.s.	kV, peak	kV, peak
30/33	20	116	78	155	190
30/33	20	110	78	176	275
40/44	27	140	95	216	290
44	30·5	145	103	210	280
50/55	33·5	175	120	288	350
60/66	33·5	200	137	264	328

All values are manufacturers' data; the impulse voltages are for 1/50 microsec wave.

Table 6

TYPICAL FLASHOVER VOLTAGES OF LINE-POST-INSULATORS FOR SYSTEM VOLTAGES OF 33–55 kV

Temperature, 20° C; Pressure, 760 mm Hg

System voltage	Total leakage distance	Flashover voltage			
		Power frequency		50% impulse	
		Dry	Wet	Positive	Negative
kV, r.m.s.	in	kV, r.m.s.	kV, r.m.s.	kV, peak	kV, peak
33	29	125	75	203	250
33	40	150	92	232	310
44	45	175	110	268	350
55	53	200	125	302	410

All values are manufacturers' data; the impulse voltages are for 1/50 microsec wave.

pin- and line-post-insulators are given in Tables 5 and 6 respectively. The polarity difference with pin- and post-insulators can be almost eliminated by the attachment of a suitable horn at the lower (earthed) end of the stack. This reduces the negative impulse flashover voltage without appreciably affecting the positive value.[14]

The polarity difference for insulators and rod-gaps tends to decrease as the flashover voltage is increased above the 50% value, and becomes negligible when the time lag is less than 2 microsec.[14]

(5.9) Dispersion of Impulse Flashover Voltages

The 50% impulse flashover voltage of a rod-gap or insulator is determined by applying surges of standard waveform but varying amplitude until an estimate can be made of the value which, on the average in ten trials, gives five flashovers. The time lapse between successive surges should not be less than about five seconds.[20] This may be termed a single test. The estimates obtained from a series of such single tests made at the same place on the same air-gap within a reasonably short period of time are normally dispersed about the overall mean value. A similar dispersion is found for the mean value obtained in different laboratories on air-gaps made to a given specification. Provided that the minimum spacing is not very small, the dispersions, when expressed in terms of the percentage deviation from the overall mean, are approximately independent of the electrode spacing. Two cumulative probability curves for rod-gaps, which were obtained from a comprehensive experimental investigation,[21] but which are also applicable to insulators and air clearances in general, are reproduced in Fig. 5.

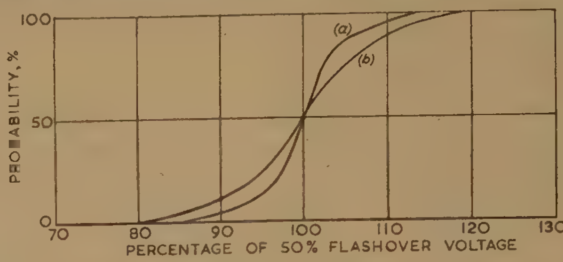

Fig. 5.—Probability of flashover of rod-gaps as a function of the deviation from 50% value.

(*a*) Mean value of 12 different test curves (gap spacing = 14–115 cm, both polarities).
(*b*) Same as curve (*a*) adjusted to include dispersion for location and time.
Tests were made with 1/50 microsec wave and corrected for air density and humidity.

(5.10) Insulator Protective Fittings

The power-frequency arc which frequently follows flashover caused by a transient over-voltage may impinge upon and severely damage the surface of an insulator, and, even worse, may burn through a line conductor. Protection against this hazard is provided, either by arcing fittings, which consist of horns and rings variously arranged, or by expulsion gaps.

The minimum air clearance between the electrodes of arcing fittings is usually about 80% of the direct air path between the metal at each end of the insulator, and this provides a shorter air path for the discharge out of contact with the insulator and the line conductor. Arcing fittings afford no protection to the porcelain in the event of a power-frequency discharge due to polluted surfaces, or when cascading occurs as a result of heavy rain, but still serve to protect the insulator hardware and line conductor under these conditions.

Expulsion gaps (or protector tubes) are seldom used as a means of protection for line insulation in general, but are sometimes used at particularly vulnerable positions or for apparatus connected to the line.

(5.11) Effects of Rain

In the presence of rain the power-frequency flashover voltage suffers a reduction which varies from about 10% for standard rod-gaps to as much as 40% for insulators without arcing fittings.

A reduction of the impulse flashover voltage in the wet condition is not generally accepted; it is probably less than 5% for rod-gaps and 10% for insulator strings,[6] but the range between the voltages for zero and 100% probability of flashover may be increased. In the presence of rain there is also an increased tendency for the discharge to cascade, especially with steep-fronted waves and breakdown on the wavefront; the discharge may terminate on the arcing-fitting electrodes whilst cascading over the central units of the string; this may be a source of trouble in tropical regions when severe lightning and heavy rain occur simultaneously.

(5.12) Wood Pole Systems

The insulation level of a line may be increased economically by using wood poles and cross-arms, eliminating earth wires and earthed metal fittings, and increasing the separation of the phase conductors. The increase obtained is approximately equivalent to 50 kV per foot of wood between line and earth in the wet condition. An all-insulated line of this type merits considera-

tion, especially when a low earth resistance is unobtainable, but the protection of station apparatus is thereby made wholly dependent on surge diverters, or, possibly, rod-gaps with auto-reclosers.

If the earth resistance is low enough, the higher insulation provided by wood poles with unbonded and unearthed metal fittings may be utilized without sacrifice of the earth-wire screen, the down leads from which may be offset and insulated from the pole, to give improved performance in regions where lightning is exceptionally prevalent.

Some typical data on wood-pole insulation levels are given in Table 7.[22]

Table 7

Typical 50% Impulse Flashover Voltages for Wood-Pole Lines (+) 1·5/40

Temperature, 20° C; Pressure, 760 mm Hg

Nominal voltage of system	Number of 10 in-diameter insulators with $5\frac{3}{4}$ in spacing*	Length of wood path	Flashover voltage (conductors to ground)	
			Dry condition	Wet† condition
kV, r.m.s.		ft	kV, peak	kV, peak
66	4	5·5	986	630
	5	5·5	1 040	700
	6	5·5	1 090	773
110	6	6	1 150	793
	8	6	1 240	925
	10	6	1 350	1 070
132	8	7	1 350	975
	9	7	1 400	1 050
	11	7	1 520	1 190
165	9	7·5	1 470	1 080
	10	7·5	1 520	1 140
	12	7·5	1 630	1 280

* Middle value represents most common practice; upper and lower values indicate range for modern lines.
† Calculated by reducing impulse flashover for the insulators by 20% and adding 50 kV per foot of wood.

(5.13) Clearances

When the minimum linear dimension of two insulated conductors, remote from extensive earthed objects, is small compared with their separation, the flashover voltage approximates to that of a rod-gap of the same separation. This provides a reasonable guide to clearances, and one proposal[15] is that, on systems operating at 33 kV and above, the minimum distance between an overhead-line conductor and a steel tower shall be the same as the spacing of a standard rod-gap which has a 50% impulse flashover voltage which is 10% greater than that of the insulator string in the dry condition (see Fig. 6). The 10% margin is introduced because it is better that flashover should occur across the insulator metal than between conductor and tower. With wood-pole systems in which the metal supporting fittings are not bonded to the earth connection, the earth clearance should be based on the flashover voltage of the insulator alone without an added margin, because it is preferable that a flashover to earth should occur to the earth connection and not across the insulator and along the wood.

The angle of insulator swing to be assumed as a basis for the estimation of clearances at suspension towers is still unsettled. An over-estimate of the probability that unfavourable factors, e.g. conductor icing, high wind velocity, lightning, etc., occur at the same time will lead to the adoption of clearances which are unnecessarily high and therefore uneconomic. The theoretical values for the maximum swing of insulators from the vertical for

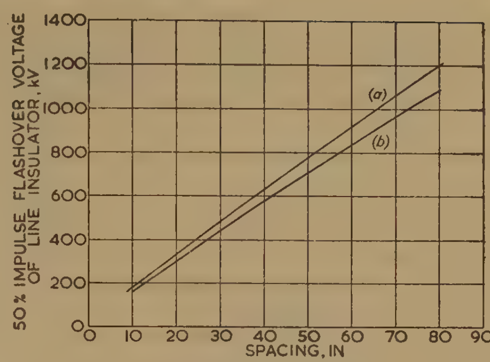

Fig. 6.—Minimum air clearances for overhead lines based on 10% margin over equivalent rod-gap.
(a) Rod-gap spacing at 20° C, 760 mm Hg, positive wave.
(b) Minimum air clearance for line insulation level plus 10%.

level ground and an assumed wind of 50 m.p.h. on some typical bare conductors are as follows:

For $0\cdot1\ \text{in}^2$ equivalent, aluminium alloy, 59°.
For $1\cdot175\ \text{in}^2$ equivalent, s.c.a., 42°.
For $0\cdot25\ \text{in}^2$ equivalent, copper, 23°.

(6) SELECTION OF INSULATION LEVELS FOR OVERHEAD LINES

In this and Section 7 the 50% impulse flashover voltage with 1/50 microsec wave will be used as a measure of the line insulation level. This value is usually called for in insulator specifications, and the uncertainty about flashover with surge voltages within about ±10% of this value is of negligible importance for present purposes.

An essential requirement is that line insulation under adverse conditions arising from atmospheric pollution, fog and rain must withstand all over-voltages which are produced in the system itself by switching operations or by a phase-to-earth fault. For this reason the insulation levels for normal system voltages above about 300 kV are not determined by lightning over-voltages. For lower system voltages it is uneconomic to insulate the line to the degree which would eliminate flashover due to lightning over-voltages of more than moderate amplitude.

The minimum standard required is such that the line insulation under wet conditions will withstand a power-frequency voltage of three to four times the nominal phase-to-earth operating voltage, and this normally ensures that the impulse withstand voltage is about the same as, or exceeds, the I.E.C. standard insulation level.

To avoid excessive demands on the station protective level, the line adjacent thereto should be protected and the amplitude of incoming surges should be kept as low as possible. The line insulation level should therefore be approximately equivalent to the standard insulation level of the system over a length which extends to at least one mile from the station, and this length should be adequately screened by one or two earth wires.

At distances exceeding a mile from the station the best value to prescribe for the line insulation level can be estimated only after consideration of the factors already described and a predetermination of the lightning performance.

Methods of calculation described in Section 7 can be used to obtain estimates of the probable outage frequency per annum for lines having a given insulation level, or, alternatively, for the line insulation level required to hold the outage frequency below a prescribed maximum.

(7) ESTIMATION OF LINE PERFORMANCE

The estimation of line performance with respect to direct lightning strokes when the line is shielded by one or more earth

wires depends on the predetermination of the probable frequency of back-flashovers at towers and at mid-span. Two methods have been developed for this purpose; they are here referred to as the E.R.A. method, which is based on studies by Golde,[9] and the American I.E.E. method, which is the work mainly of Harder and Clayton.[8] These methods differ in certain details but show fair agreement in the outcome, so that such past records as permit application of an analysis cannot be quoted as being more in favour of one than the other.

In any case, from the nature of the problem, high accuracy in an absolute sense cannot be expected, but fair relative accuracy may be claimed, so that either method should give a reliable estimate, at least, of changes in performance which may be expected to result from modifications of the line insulation level and certain other parameters of a given overhead-line system.

The fundamental step is the determination of the potential rise of the tower, when lightning strikes the tower top or the earth wire, as a function of the lightning current, for a range of values of tower footing resistances and span lengths. In the E.R.A. method this function has been derived from first principles. The numerical calculations are laborious and only two span lengths (885 and 442·5 ft) have so far been considered; these particular values were chosen to simplify the work, but they are representative of spans used for systems of present interest.

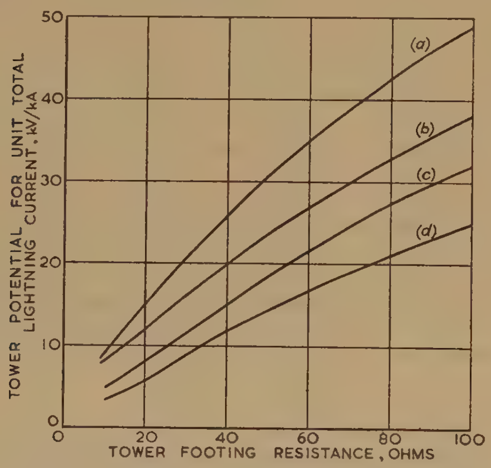

Fig. 7.—Tower potential for unit total lightning current as a function of tower footing resistance for typical h.v. lines.

(*a*) Strokes to tower, 885 ft span.
(*b*) Strokes to tower, 442·5 ft span.
(*c*) Strokes to mid-span, 885 ft span.
(*d*) Strokes to mid-span, 442·5 ft span.

Fig. 7 shows the results of these calculations, the tower potential appearing as a multiple of the total lightning current. To obtain the voltage drop across the insulator, the tower potential must be multiplied by $(1 - C)$, C being the coupling factor.[6, 15]

For a given line-insulation level there will thus be a corresponding value for the minimum lightning current which will cause flashover, and the probability, p, that this current will be exceeded in a given number of lightning strokes may be obtained from Fig. 2. In a strict calculation there should be an adjustment for waveform, but the correction required is not known with certainty, and since it is relatively small it may be ignored.

The number of strokes, N, terminating on each hundred miles of the line per year is calculated from the known isoceraunic level and the line parameters by use of the appropriate equations given in Section 2.4. The number of lightning flashovers then follows as the product pN.

Predeterminations of the lightning performance of two typical transmission lines for a range of line parameters, which have

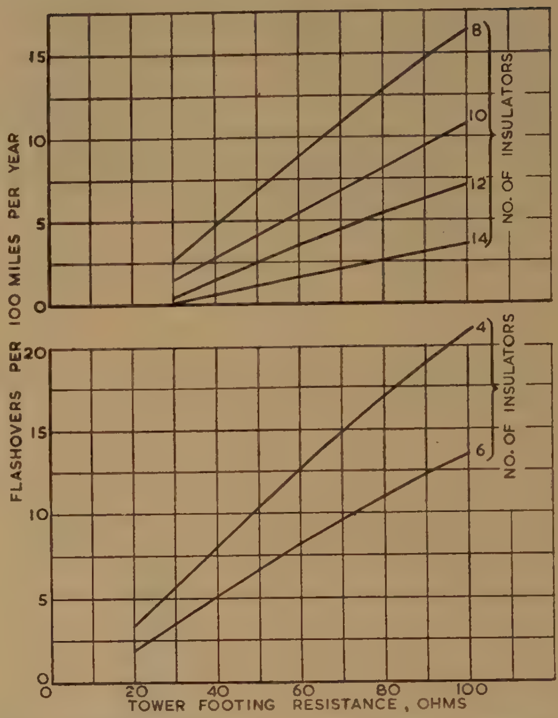

Fig. 8.—Lightning performance of two typical transmission lines according to E.R.A. method (isoceraunic level = 30).

(*a*) Span, 885 ft; strokes to line, 67 per 100 miles per year.
(*b*) Span, 442·5 ft; strokes to line, 52 per 100 miles per year.

been made in accordance with the foregoing procedure, are presented in Fig. 8.

In the American I.E.E. method the potential rise of the tower top due to a lightning stroke to the tower or the earth wire at mid-span is obtained by using an analogue computer, and the strokes-to-line frequency is based on the American I.E.E. data referred to in Section 2.4.

The results of applying these two methods in a particular case of a conventional type of line are compared in Table 8. In this case the following line parameters were assumed: line insulation level (insulator string with 10 discs), 960 kV; isoceraunic level, 30; tower-footing resistance, 80 ohms; coupling factor with corona present, 0·45.

Table 8

COMPARISON OF LIGHTNING PERFORMANCE OF TRANSMISSION LINES WITH 885 FT SPAN CALCULATED ACCORDING TO AMERICAN I.E.E. AND E.R.A. METHODS

Method	Lightning-strokes to line per annum		Total flashovers of line per annum
	To towers	To mid-span	
A.I.E.E. ..	50	50	11·5
E.R.A. ..	24·6	41	8·0

The procedure for the converse problem of deriving the line insulation level required to give a prescribed lightning performance is sufficiently obvious.

On overhead lines not shielded by earth wires and having an impulse insulation level not higher than about 1 000 kV, all lightning strokes exceeding a few hundred amperes which termi-

nate on phase conductors will invariably cause flashover to the adjacent tower or neighbouring phase conductor. On such systems, therefore, the flashover frequency with respect to strokes-to-line is the same, according to the E.R.A. method, as the strokes-to-line calculated from eqn. (1). The effective surge impedance of the line at the point struck may be taken as approximately 250 ohms, so that the proportion of strokes-to-line producing flashover is easily calculated from the lightning-current probability curve and the insulation level concerned.

According to Golde,[7] strokes to towers with no earth-wire protection can be treated similarly, the effective impedance presented to the discharge being equal to the tower footing resistance increased by approximately 10% when less than about 40 ohms, in order to include the effect of tower inductance.

Systems with earth wires below the phase conductors do not differ in behaviour with regard to flashover caused by strokes-to-line from systems with no earth wire.

Flashovers of the line such as have been considered in the foregoing are not invariably followed by a power arc even where there is no fault-current limitation, as with effectively earthed systems, and therefore the outage frequency is likely to be somewhat lower than the flashover frequency. According to American records the proportion is 0·85 for h.v. steel-tower lines of less than 100 miles in length and between 0·35 and 0·5 for wood-pole lines.

On a system with resonant earthing of the neutral, single-phase flashover to earth will not normally cause outage, but the arc-suppression coil is frequently paralleled by a short-circuiting switch to interrupt persistent earth faults. Resonant earthing is ineffective if more than one phase is involved.

(8) AUTOMATIC HIGH-SPEED RECLOSING SWITCHGEAR

The damage to line insulation caused by flashover of a surge is usually of small importance and operating experience indicates that about 80–90% of outages due to line flashovers can be successfully reclosed. High-speed relaying and rapid-action circuit-breakers are effective in preventing the damage which can be caused by the 'follow' arc. Hence it is to be expected that such switchgear, with the addition of a high-speed reclosing mechanism, could be used with advantage on h.v. overhead-line systems and would greatly reduce outages caused by lightning over-voltages. The use of this type of switchgear is becoming widespread in the United States, but has not been applied to any great extent in Europe.

On h.v. distribution systems automatic high-speed reclosing switchgear has been designed for a clearing time of three half-cycles with reclosure after six half-cycles, and on e.h.v. lines with high short-circuit capacity the reclosure times are from twenty to thirty half-cycles.

(9) ACKNOWLEDGMENTS

The paper is the outcome of preliminary discussions with Messrs. P. J. Ryle and N. G. Simpson, to whom the authors are greatly indebted for advice on presentation and subject-matter. The authors gratefully acknowledge the valuable information and suggestions contributed by Dr. J. S. Forrest, Dr. R. H. Golde, and Messrs. G. W. Bowdler, G. H. Gillam, L. Gosland, N. E. P. Harris, H. M. Lacey and W. G. Standring. Acknowledgments are also made to Ernest Benn Ltd. for permission to reproduce the world map in Fig. 1, and to the British Electrical and Allied Industries Research Association for permission to publish the paper.

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[The discussion on the above paper will be found overleaf.]

DISCUSSION BEFORE THE SUPPLY SECTION, 19TH DECEMBER, 1956

Mr. N. G. Simpson: It is well to reflect that transmission line design is dominated by structural considerations which are largely known. Structures can in fact be designed to sustain within fine limits their specified external loads. The outstanding problem, therefore, is to decide on the correct ultimate external loads to be used for design purposes. Ice and wind may be the principal components, and although the latter is determinable enough, the former can build up to uneconomic proportions. Such external loads have to be treated realistically on a 'limited liability' basis.*

In temperate zones the prospect of ice loads has a large influence on the design of transmission lines, while lightning is of less significance. In tropical and sub-tropical regions, however, there is no ice problem but that of lightning becomes predominant. In other words, the structural hazard recedes in favour of an electrical one, and incidentally, the same attitude of limited liability insulation value or the co-ordination of these and other features in one structure may be a potential cause of shut-down in not one but possibly 500 structures in a run of 100 miles.

Emphasis should perhaps be laid on the more logical method of estimating the number of strokes to line on the basis of area covered by the line, as compared with the American method which assumes that this number is independent of tower heights and therefore of the area covered. Similarly, the smaller proportion of cloud–earth strokes in the tropics is an important issue, since it may be inferred that, although the isoceraunic level in the tropics may be high, the effective level for design purposes may be taken as two-thirds of the actual, with resulting economies. Could the range of territories be named where such 'relaxations' are warranted?

Present methods of estimating likely line outages due to

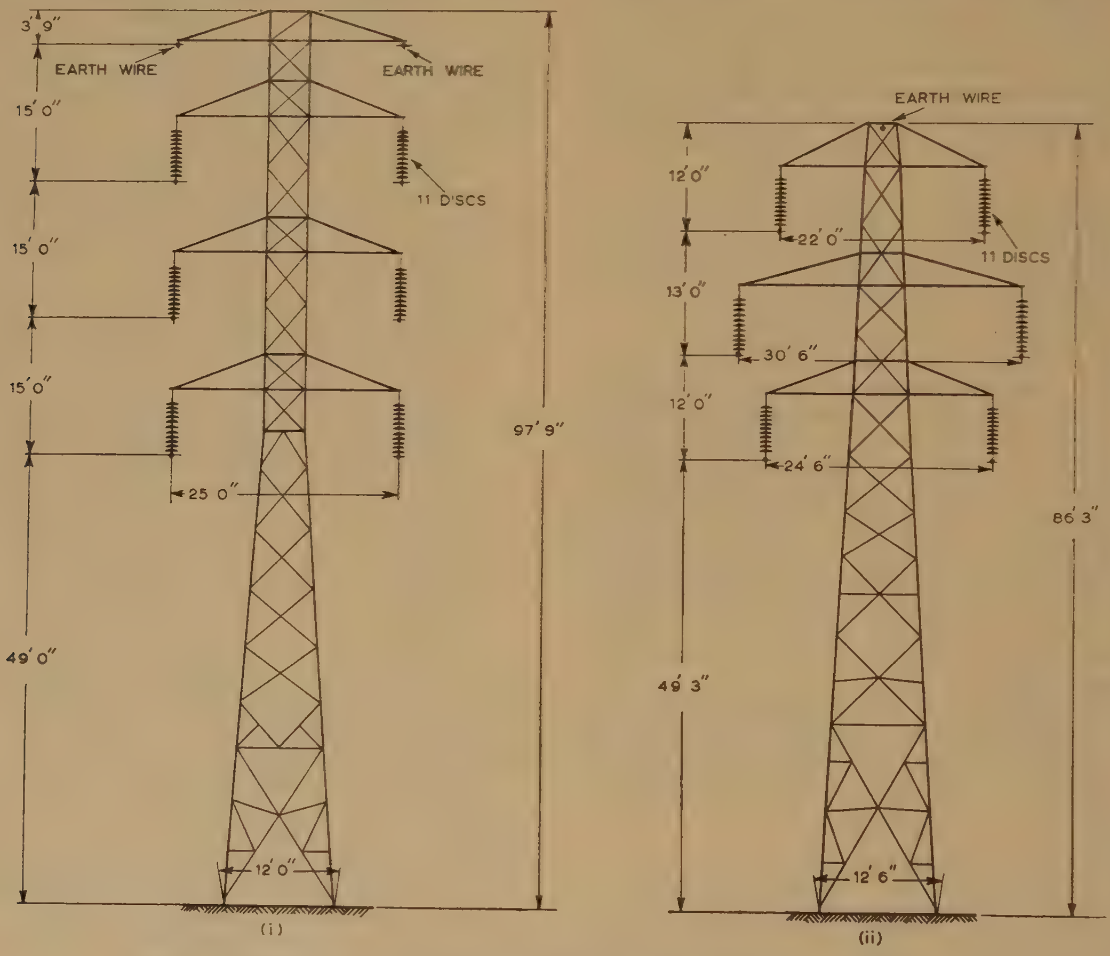

Fig. A.—Outline comparison between a British Grid and a Uganda 132 kV tower.
(i) Uganda Electricity Board 132 kV d.c. line, D2° type tower.
(ii) British Grid 132 kV d.c. line, D2° type tower.

must in most cases be applied. Fig. A gives an outline comparison between a British Grid and a Uganda 132 kV tower. The latter support is slender, owing to the absence of ice loading, has greater insulation value, structure clearances and earth-wire protection, and altogether there is a marked consideration for the protection of the circuits against lightning. It must be remembered that with transmission lines a small deficiency in clearance, lightning exemplify the human tendency to adopt available formulae without investigating too deeply their reliability and limitations, and it is well, therefore, to retain a sense of proportion. Such methods have still to withstand the test of time and statistical analysis, particularly on new lines erected in tropical zones.

Recent reports from the United States indicate that lightning outages on some of their e.h.v. lines are far more numerous than estimated by current methods. The authors refer to aspects of

* Boyse, C. O., and Simpson, N. G.: 'Conductor Sagging on Overhead Transmission Lines,' *Journal I.E.E.*, 1944, 91, Part II, p. 219.

steel-tower inductance, and insufficient regard to this might well explain the wide disparity.

Assuming, for example, a lightning current of $\frac{1}{40}$ microsec waveshape and 50 kA amplitude discharging through two towers 100 ft and 200 ft high, with a tower inductance of 10 μH per 100 ft and a footing resistance of 10 ohms each, the tower-top potential (developed after 1 microsec) may rise to

$$\left.\begin{array}{l}500\,\text{kV (resistive drop)} + 500\,\text{kV (inductive drop)} \\ \qquad \simeq 1\,000\,\text{kV}\end{array}\right\}\text{for 100 ft tower}$$

$$\left.\begin{array}{l}500\,\text{kV (resistive drop)} + 1\,000\,\text{kV (inductive drop)} \\ \qquad \simeq 1\,500\,\text{kV}\end{array}\right\}\text{for 200 ft tower}$$

As the tower potential is given by the expression $v = iR + Ldi/dt$, with a steeper current wavefront the proportion of inductive drop will be even greater.

The insulator flashover characteristics will determine the actual flashover conditions, but the above example brings out the significance of tower inductance.

In the distribution group of lines the problem of lightning protection is even more difficult and complex. It is, however, just as necessary to resolve, if only because of the overall greater length and maintenance problem. Here, again, experience must weigh heavily in the long run. For example, no one can at present say which gives the best operating performance in tropical zones, unearthed wood-pole lines, semi-earthed wood-pole lines with earth-wire screen, or a fully earthed line with fully earthed metal supports.

Mr. R. Davis: In Section 5.4 it is claimed that air flashover is a function of absolute and not relative humidity, but the warning is added that tests should not be made at relative humidities above 95%. Comprehensive evidence of the humidity effect would be of great value.

The authors show it is possible, in principle, to design an overhead line to have a given number of flashovers per year, but give no guidance as to what the number should be. If the number of flashovers for line A is much greater than for an alternative line B, there will be greater risk of supply interruption with A but greater risk of damage to expensive terminal equipment with B. I doubt if one can properly consider the surge protection of overhead line divorced from the terminal equipment connected to the line.

Terminal equipment is usually protected by the use of special gaps or surge diverters; lengths of cable inserted between the line end and station can also contribute. Dangerous voltages at a station arising from lightning can be produced by the following conditions:

(*a*) Voltage drop in the earth resistance subsequent to line flashover.

(*b*) Flow of lightning current into the line up to the instant of line flashover.

(*c*) Flow of current into a line which does not cause line flashover.

For perfectly shielded lines only incidents in (*a*) associated with back flashover are possible.

To calculate the frequency of dangerous voltages at a station, a lightning current of amplitude I is selected, and the maximum distance x from the end of the line at which this current must occur to produce a dangerous voltage due to current flow in the earth resistance subsequent to line flashover ray is determined. This procedure is carried out for different values of I. Data are available giving the frequency N per mile-year of lightning currents exceeding I, and if N is plotted as a function of x, integration of the curve gives the number of station incidents associated with this category of event. The same procedure can be followed for the other two categories. The calculation is based on a number of assumptions, e.g. lightning current waveform and wave attenuation in travelling the distance x. To assess the contribution of cable to station protection it can be assumed to behave as a lumped capacitance in parallel with the station capacitance. Detailed calculations have been made.*

Analyses of lightning fault statistics by the E.R.A. suggest that the protection by a length of cable is not as effective as calculation indicates, and it may prove necessary to re-examine the basic assumptions.

Dr. J. S. Forrest: The number of lightning flashes to earth per square mile is of primary importance in estimating the lightning performance of overhead systems.

In Section 2.3 it is stated that the number of cloud–earth strokes per square mile per year is roughly half the isoceraunic level in temperate zones. Fig. 1 also gives information on the lightning flashes to earth per square mile, but it is important to note that the data given in this Figure are not independent evidence—the map was prepared by Brooks from his original 1925 map of thunderstorm-days by making the same assumptions as the authors of the present paper: (*a*) that the number of cloud–earth strokes is proportional to the isoceraunic level, and (*b*) that the factor of proportionality is one-half in temperate zones.

The first is contrary to experience; for example, if there are twice as many thunderstorm-days, we find that there are more than twice as many breakdowns due to lightning. In addition, Mr. Ryle has pointed out† that experience on the lightning performance of lines in South Africa also suggests that the number of lightning faults increases more rapidly than the isoceraunic level. The same trend was found in Canada by the Hydro-Electric Power Commission of Ontario.

The second assumption means that on the average there should be six lightning strokes to earth per square mile per year in this part of the country. Attempts have been made for some time to obtain reliable data on this point but the difficulties have been very great. Experiments made with a field-measuring instrument designed by Gane and Schonland have had little success in this country. Another approach is to record the waveform of the atmospheric discharges and to identify the cloud–earth strokes within a given distance. The waveforms recorded are very diverse, however, and definite identification of cloud–earth strokes is not easy. It is also difficult to measure the distances of the individual strokes, and this can lead to large errors since the square of distance is involved in the estimate of the strokes to earth per square mile. However, Wormell and Pierce at Cambridge have been very successful in this work and have concluded that in the Cambridge area there is approximately one stroke to earth per square mile per year.‡

If the rule given in the paper is correct, each of us should experience six flashes to earth every year on the average within a square mile. One or two seems to be more in accordance with actual experience.

It appears, therefore, that our estimates of the number of cloud–earth flashes vary over a range of about 6 to 1, and that all calculations and estimates based on eqn. (4) of the paper will be subject to this uncertainty until we are able to get reliable information on the number of lightning flashes to earth. I would welcome the authors' comments on this.

Dr. R. H. Golde: The ratio of the frequency of lightning flashes to the number of thunderstorm days in temperate regions (i.e. 1 : 2) was derived by a careful analysis of American statistics, as reported in Reference 9, and a further investigation of British observations.§ The corresponding ratio for tropical regions (i.e.

* Davis, R.: 'Station Protection by a Length of Cable', E.R.A. Report S/T62.
† Ryle, P. J.: *Quarterly Journal of the Royal Meteorological Society*, 1950, 76, p. 467.
‡ Wormell, T. W.: *ibid.*, 1953, 79, p. 3.
§ Golde, R. H.: *ibid.*, 1945, 71, p. 89.

1 : 3), on the other hand, is based on no more than an intelligent guess. In the circumstances, no undue reliance should be placed on Fig. 1 until more reliable information becomes available, particularly for tropical regions. It is hoped that such information may be forthcoming from a novel lightning-stroke counter* which is at present being developed.

In Section 2.2 the authors convey the impression that the severest stresses to which substation equipment may be subjected are due to direct lightning strokes to a phase conductor. I would suggest that even higher stresses may be produced by back flashover near a substation, since such surges are characterized by very high amplitudes and an almost infinitely steep wavefront at the point where back flashover occurs.

In the authors' Reference 5 the waveshapes of the potentials are determined which arise at the top of a tower of normal height as the result of a direct lightning stroke. These waveshapes may deviate notably from the standard $\frac{1}{50}$ microsec wave. I suggest that they should, and could, be taken into account when estimating the lightning performance of a transmission line. The effect of this simple refinement will be found to be by no means negligible.

Mr. R. A. York: Lightning performance on overhead lines is not wholly unimportant in this country, as more and more important loads of large magnitude rely on overhead lines for their supply.

With lines of 66 kV and 33 kV two problems arise. First, we have to provide a line as economically as possible, and secondly, the line has to be as lightning-free as possible. In the past few years this has largely been achieved with the wood-pole construction with unearthed steelwork. Do the authors feel any worthwhile improvement could be effected economically by replacing all steelwork by an insulating material?

Whatever design of line is installed it will by no means be lightning-proof, and the next serious problem encountered is the effect of outages caused by lightning. As far as these are concerned, a great improvement could be effected by the use at these voltages of high-speed automatic-reclosing circuit-breakers. We have little experience of these devices at 66 kV and 33 kV in this country, but on some 11 kV networks in the midlands we have now had a year's experience. Of the 176 operations of a number of these reclosers, only four cases of persistent damage arose; i.e. only just over 2% of the faults were of a persistent nature compared with a figure of 15% which is normally expected. This has been chiefly because rapid interruption of the follow current has limited the amount of damage which has been done to insulators and the like.

I applied two of the formulae in Section 2.4 for estimating the probable stroke-to-line frequency to 66 kV lines, in order to compare the results with the actual number of lightning incidents which were reported in the years 1950–54. For unearthed wood-pole lines the number of lightning incidents per 100 miles of line per year, as calculated by the formulae, corresponds closely to the calculated number of strokes using the factor of 0·35 referred to later in the paper. With steel-tower single-circuit lines with overhead earth wires, however, the number of incidents was only about one-tenth of what would have been expected using the factor of 0·85.

Although the authors express no preference for glass or porcelain as insulators, I consider that the inherent properties of the glass insulator make it a better proposition for suspension insulators.

Mr. D. M. Cherry: For higher voltages, the authors have paid too much attention to the lightning aspect and too little to the power-frequency aspects, which often have a greater effect on the dimensions affecting the tower design and hence on the cost of the line. According to the authors the addition of an extra insulator disc makes little difference to the lightning performance at the higher voltages; nevertheless, it appreciably affects the cost of the towers.

They suggest that the expected stroke frequency in relation to the isoceraunic level should be reduced by two-thirds for the tropics, where the level is high. In the same Section they suggest that the number of strokes is proportional to the isoceraunic level raised to a power greater than unity. Evidence from the Belgian Congo supports the first suggestion, but the relation may depend in fact on the type of storm prevalent.

The reference to the I.E.C. standard insulation levels as a guide to line insulation is misleading. These levels are primarily intended for apparatus protected by lightning arresters, and there are two levels for each system voltage, depending on the degree of protection possible. The power-frequency figures admittedly include wet withstand conditions, but such relatively low wet withstand voltages would not normally be applied to line insulation.

There is sufficient statistical information available on the protective value of earth wires to justify much fuller treatment in the paper. Properly disposed earth wires appear to reduce fault incidence by 90%, but the cost of this addition is considerable, particularly for light types of line construction used oversea. In such cases high-speed auto-reclosing should be considered as a cheaper alternative, and one that will also deal with some of the faults that the earth wire cannot prevent.

The authors are optimistic in basing their clearance figures on a withstand value of approximately 14 kV per inch. Recent tests in this country on practical configurations gave 50% flashover values of about 15 kV per inch. As the configuration is markedly asymmetrical, the dispersion is large, and for a genuine withstand value a figure of 12½ kV per inch is more appropriate.

Section 7 is of very doubtful value at the higher voltages. In practice, system operation engineers cannot be persuaded to say what fault performance they will accept. The only figure really acceptable to them is zero faults per 100 miles per year. Accordingly estimates of line performance are of little value, except for comparative purposes. Further, it is now clear that, for lines with high towers, estimates made by the methods shown in the paper will be greatly in error, by reason of the flashovers caused by steep-fronted strokes and the material inductance of the tower for such strokes. Little reference is made to this type of flashover in the paper, although it is one of the most important recent developments, and so far has no obvious remedy. Unless the authors can suggest something better, it would seem necessary to apply high-speed auto-reclosing on lines subject to these flashovers. In any case, the value of high-speed auto-reclosing as an aid to economy in line design requires more consideration than it has received in the paper.

Dr. C. H. W. Clark: The choice of insulation for an overhead line is not clearly described in the paper, and an example of a typical case would have been useful. A suitable insulation level, expressed in terms of test voltages and leakage distances, could be derived for a typical line, assessing its importance in terms of number of outages per year to be tolerated, and assuming an isoceraunic level and the degree of pollution in different parts of the line.

The problem could conveniently be considered in three parts:

(*a*) Insulation level, as expressed by power-frequency dry and wet withstand or flashover test voltages. This aspect has been given most prominence in the past, e.g. in B.S.137.

(*b*) Pollution; here the shape and size of the insulator is important, but its performance cannot be assessed in terms of test voltages. Creepage distance is probably the best criterion.

* Pierce, E. T.: *Archiv für Meteorologie, Geophysik und Bioklimatologie*, 1956, 9, p. 78.

(c) Impulse insulation level, an aspect which has been well treated in the paper.

Each aspect should be considered separately; depending on conditions, any one may be the critical consideration, the insulators chosen from this aspect being more than adequate from the other two points of view.

In Section 5 the authors refer to 0% and 100% flashover values. These figures are not commonly used and I hope that they will not become so. Referring to Fig. 5, they represent the voltages at which the S-curve intersects the 0% and 100% lines, values which are obviously very indefinite.

It has been claimed that the long-rod insulator gives a better performance in polluted atmospheres because, when coated with deposits having a given surface resistivity, its total resistance is high owing to its small diameter. It would be interesting to know whether comparative tests on long-rod and other types of insulator having the same creepage distances support this contention. It has been said that the low capacitance of the long-rod insulator is a disadvantage under pollution conditions, but it is doubtful whether the capacitance of cap-and-pin units is sufficient to have any appreciable grading effect. The low capacitance of the long-rod insulator enables it to provide a complete solution to the problem of corona on insulators at very high voltages. This may, however, be of very little importance, since at very high voltages corona on the line conductor is usually a far bigger source of radio interference than corona on the insulators.

Another claim for the long-rod insulator is that it can be more fully protected against damage by power arcs. This is based on laboratory tests, but these carry considerable weight, provided that conditions, including wind, are carefully imitated, because this is not the type of test where one has to alter the time scale and try to determine in a short time in the laboratory what may happen as the cumulative result of many years' service.

The authors mention in Section 5.9 that the time lapse between successive shots during impulse-flashover tests should be 5 sec, the intention being, I believe, to allow charges which may collect on the insulator surface in dry weather to leak away. Laboratory experience shows that no significant error arises when tests are carried out much more rapidly. Normally the most rapid convenient rate of firing an impulse generator would be with one- or two-second intervals, and I consider it wrong to specify any slower rate of working.

Impulse-flashover tests under rain are briefly mentioned and more data are required. Most insulators have a considerably higher dry impulse-flashover voltage with surges of negative polarity than with positive. I have found that under rain this difference tends to be reduced, the negative impulse-flashover voltage being lower and the positive flashover voltage higher. This means that the withstand test voltage is higher if the test is made under rain.

Mr. F. S. Edwards: No reference is made to the humidity corrections prescribed by the A.S.T.M., which are calculated on a rather different basis from those quoted in Table 1. The difference between the two may be appreciable and represents an uncertainty in the flashover voltage.

I think it would add to the usefulness of the Tables if the coefficient of variation of the flashover voltages and the effect of time on the results could be stated. This remark applies with special force to the tests under rain.

If it is intended to apply the data given in the paper to the design of overhead lines, it is most important to know the test conditions and the degree of inaccuracy or scatter which may be expected in the results.

Mr. W. T. J. Atkins: The design of engineering structures often involves an assessment of risks arising out of variable climatic conditions. For example, it is customary to refer to estimated flood levels as those which might be expected to occur once in so many years. Would it not be equally desirable, in studying the effects of lightning, to take formal account of its variations in severity from one year to another?

Mr. H. E. Green (*communicated*): The curve in Fig. 2 which shows the frequency distribution of lightning strokes of various amplitudes can be represented as a straight line by being drawn on logarithmic-probability graph paper. This is illustrated in Fig. B.

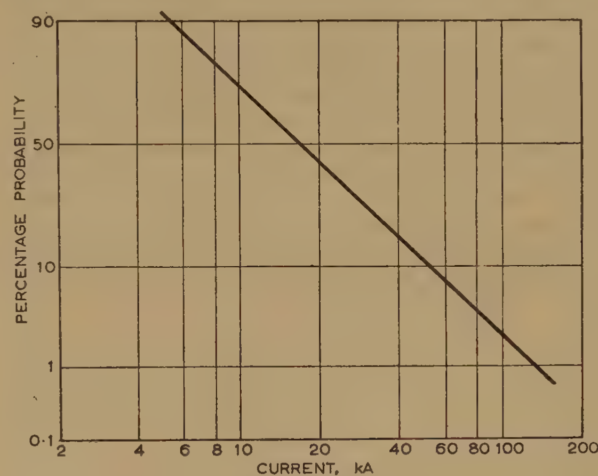

Fig. B.—Frequency distribution of lightning strokes of various amplitudes.

It may be that the S-curves shown in Fig. 5 can also be converted to straight lines in a similar manner, in this case by using arithmetic (linear) probability paper.

In Section 2.2 it is stated that induced surges are of no practical importance on systems operating at about 33 kV and above. I was, however, under the impression that such induced surges could attain an amplitude of 400 kV with a steepness of 50 kV per microsec. If the line terminates at an apparatus of high surge impedance this could, by reflection, reach a value nearly double, i.e. approximately 800 kV, and would therefore correspond to a system voltage somewhere between 150 and 220 kV.

Referring to the isoceraunic level, this is defined as the number of days in a year on which thunder is heard. Since this figure may vary from year to year, e.g. it may be 30 in one and 60 in another, I would suggest that the average be referred to in the definition, this average being obtained over a period of not less than 10 years.

Mr. W. J. Nicholls (*communicated*): Section 3 deals with shielding by earth wires, and Section 4 emphasizes the importance of low earth resistance. No reference is made to the resistance of the earth wire itself. This can vary from 5 ohms per mile for a steel earth wire, commonly used abroad, to 0·5 ohm per mile or even less for the s.c.a. earth wires used in this country. Could the authors indicate whether the lower-resistance earth wire is effective in protecting the lines from lightning over-voltages and, if so, to what extent?

In Section 5.13 the angular displacements quoted as the maximum swing of insulators apply strictly to the conductors only. Because the insulators have considerable weight they will not swing as much as the conductors and the theoretical swings of the insulators, assuming normal insulation, would be

$0\cdot1\ \text{in}^2$ equivalent, aluminium alloy ..	57°
$0\cdot175\ \text{in}^2$ equivalent, s.c.a.	$39\frac{1}{2}$°
$0\cdot25\ \text{in}^2$ equivalent, copper	23°

Mr. J. M. Stock (*Uganda: communicated*): Experience of the special problems arising in tropical conditions is very limited and only passing reference is made to them in the paper. I would suggest that much greater use might with advantage be made by investigators in the United Kingdom of operators oversea who would be willing to co-operate in research. This might be especially valuable in relation to lightning research. For instance, the Uganda Electricity Board is operating overhead lines at 132 kV, 66 kV, 33 kV and 11 kV in an area in which the two meteorological stations (Entebbe and Tororo) have recorded average isoceraunic levels in the years 1953–55, of 218 and 189, respectively. Data are being collected by the Board, and no doubt by other oversea operators, but the value of such data would be much greater if collection were directed and the results co-ordinated by some central organization such as the E.R.A.

Mr. J. H. Sumner (*Kuala Lumpur: communicated*): With regard to the prediction of lightning fault rates, I believe the conclusions reached by the authors have been proved sound in temperate climates where isoceraunic level is in the range of 30–60 storm days per year. I am of the opinion, however, that although sound in principle, their conclusions may lead to inaccurate estimates of lightning fault rates for, say, lines in the tropics or in South Africa.

For some years I have been investigating the lightning fault rates of 66 kV lines in Malaya, where we have an average isoceraunic level of about 180 storm days per year. Most of the thunderstorms occur in the afternoon, and there are two bad seasons per year depending on the incidence of the N.W. and S.E. monsoons. My impression is that the cloud base in Malaya is much lower than in temperate climates, and also *per storm* we seem to get many more flashes from cloud to ground than would be the case in, say, the United Kingdom. The flashes are usually thick and straight, and many of them are multiple strokes. In the Malayan tropical areas I suspect, therefore, that our fault rates will prove to be larger than would be predicted by assuming a *pro rata* relationship between the isoceraunic level and the fault rate.

In South Africa, on the other hand, I understand that the cloud base is usually high, and Schonland I think has stated that a high proportion of cloud–cloud flashes occur during African storms. Therefore, in South Africa one might expect the lightning fault rate to be less than proportional to the isoceraunic level. This appears to be borne out by General Report No. 3 on transmission networks at the recent International Symposium on Electricity in the Tropics which states that the 110 kV lines in Haut Katanga operating with an isoceraunic level of 150 had a fault rate of only 0·863 per 100 km per year, whereas similar lines in America, with presumably an isoceraunic level of about 30, had a fault rate of 2·14 per 100 km per year.

I think, therefore, that the authors are perhaps on dangerous ground in suggesting that eqn. (4) can be used by putting $\alpha =$ for temperate zones and $\alpha = \frac{3}{4}$ for the tropics. The 'tropics' is a very wide and vague term, and it is unfortunately true that the largest volume of research and field investigation of lightning strokes to transmission lines has been done in temperate climates, mostly in the United States.

In my investigation of lightning fault rates in Malaya I have as yet only 4 years' fault data properly analysed. I feel that it would be wise to accumulate, say, 5–6 years' operating results before attempting to draw any reliable conclusions from data containing so many 'unknown' factors.

Mr. D. H. Tompsett (*communicated*): It has been suggested that lightning-performance statistics from as many sources as possible should be compared with predicted figures based on the line data and the formulae quoted in the paper. The different line parameters number at least 12, so that any such accumulation of comparative calculations would prove extremely time-consuming (see a remark of the authors in Section 7). There can be no doubt, however, that great progress would follow such an investigation, especially if the formulae could subsequently be amended in the most appropriate manner, giving proper weight to all the available information.

This is an ideal field for the application of modern high-speed digital computing facilities, such as exist at the National Physical Laboratory—an organization with which the authors are already in communication on electrical matters. The data for all the lines could be transferred to punched cards which could be fed into the computer with a special programme incorporating all the formulae, expressions and curves. When a sufficient number of different statistics became available, it would appear possible to apply some form of multiple regression analysis or optimization procedure to determine which terms in the formulae should be adjusted and by what increments.

The same programme would, naturally, be available for the estimation of the performance of a projected design or the determination of the required insulation level to achieve a specified outage rate. The compromise between economics and performance, already mentioned, could also be automatically included if the design and operating engineers could be prevailed upon to formulate the basis upon which their 'engineering judgment' is exercised.

[The authors' reply to the above discussion will be found on page 247.]

MERSEY AND NORTH WALES CENTRE, AT CHESTER, 19TH NOVEMBER, 1956

Mr. W. T. J. Atkins: The final proof of suitability for duty of any piece of electrical equipment must always rest on operational experience. Little reference is made in the paper to this complementary aspect of the problem. So far as lightning is concerned, systematic studies of performance have been made in this country for several years, and the authors and their associates have taken active part in the collection of statistics of faults and damage attributable to that cause. Prior to the nationalization of electricity supply, certain of the larger undertakings, particularly the Central Electricity Board, maintained detailed records of the effects of lightning on their plant. Since 1948, it has been possible to extend this work to all sections of the supply industry, and to co-ordinate methods and results on a uniform basis. The E.R.A. have properly taken a leading part in this activity, and have assumed responsibility for analysing the very large bulk of data contributed by the Central Electricity Authority and the various Electricity Boards. It is satisfactory to note that the results provide substantial confirmation of many of the statements contained in the paper. At the same time, it is important to bear in mind the variable—indeed, capricious—nature of lightning and there is perhaps not sufficient emphasis in the paper on variations of severity with time and locality, which imply that data only become significant when they are obtained through averaging a very large number of observations.

Would the authors quote the evidence supporting their statements about the relative frequencies of lightning strokes to earth in temperate and tropical climates, and about the occasional absence of power arc following an insulator flashover?

Dr. R. H. Golde: Two comments on the parameters involved in the E.R.A. method of estimating the frequency of lightning faults on high-voltage lines may be pertinent.

The average frequency of lightning flashes to earth is likely t

be related to the number of thunderstorm-days. In an endeavour to obtain reliable information on this figure for Britain a thunderstorm survey was initiated by the E.R.A. in 1948.

Eqn. (1) in the paper, by which the area can be estimated over which lightning is attracted by an overhead line without earth wire, applies to a line with steel towers or earthed wood poles. The corresponding equation applicable to unearthed wood-pole lines would read, with the symbols used for eqns. (1)–(3):

$$A_4 = b_p + 2h_p$$

In their brief reference to automatic reclosers the authors might have mentioned that persistent damage may frequently be prevented by the rapid interruption of the fault current. In particular, the cost of special protective fittings, such as mentioned in Section 5.10, could be saved if rapid reclosers were installed.

Mr. L. Csuros: The method discussed in the paper relates the probability of lightning outages to tower-footing resistance, span and line insulation level. No reference is made to the height of the towers.

Fundamental considerations indicate that at the instant of a lightning stroke the tower top can reach extremely high potential which drops only after the surge has been reflected at the tower footing and has reached the top again. This normally takes a small fraction of a microsecond, and during this period the value of the tower-footing resistance can have no influence on the potential of the tower top.

On tall towers the duration of this over-voltage may be sufficient to cause back flashover in spite of very low tower-footing resistance. This has been confirmed by laboratory tests. It appears, therefore, that if the height of the tower is ignored in the calculations, substantial errors may occur on lines where the methods discussed in the paper indicate very low fault rate. The number of lightning flashovers on the American 330 kV network has so far been about ten times as high as calculated by the methods referred to in the paper, that is by ignoring the effect of the height of the tower. Such a discrepancy does not appear to exist between calculated and actual performance on 132 kV systems, one of the possible explanations being perhaps that the number of flashovers caused by the mechanism described is very small compared with those which would occur in any case whatever the height of the tower.

I appreciate that service experience with American 330 kV and British 275 kV lines is insufficient to draw firm statistical conclusions. It appears to me, however, that the information already available suggests that the calculations referred to in the paper require revision, at least for transmission lines of 275 kV and above, so as to include the effect of tower height. I would be interested to have the comments of the authors on this point.

Mr. G. F. L. Dixon: The surge protection of overhead lines cannot be considered in isolation. We have to consider the protection of terminal equipment at the same time.

This remark has a particular bearing on the widespread introduction of unearthed lines in this country since the war. Since 11 kV lines are outside the scope of this paper the remainder of my remarks must be assumed to apply to 33 kV lines only.

Unearthed lines have various advantages, but all earthed lines (including those with under-running earth wires) share one advantage: they make the risk of damage to substation equipment small. When such lines are struck by lightning they flash over to earth near the point struck, and the resulting low-amplitude surges propagated along the line are rapidly attenuated so that they usually present little hazard to substation equipment. In the past, the incidence of equipment damage in this country was small even though most undertakings did not install many surge diverters (other than rod-gaps) on their systems. I think the position has now changed.

When lightning strikes an unearthed line, it usually flashes over between phases near the point struck, but does not flash over to earth. High-amplitude steep-fronted surges are therefore propagated towards the line-ends. Moreover, these surges suffer little attenuation and arrive at the substations at substantially full severity. Plain rod-gaps cannot be regarded as adequate protection in such cases.

To avoid an undesirable amount of damage in future it seems, at first sight, as if there are two alternatives. We can either erect lengths of earthed line near substations to act as buffers or we can install appreciable numbers of silicon-carbide surge diverters. Planning considerations rule out the first alternative as a general solution and we are left with the second.

[The authors' reply to the above discussion will be found on page 247.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 14TH JANUARY, 1957

Mr. A. B. Wood: The method proposed by the authors follows conventional lines but has unfortunately not been continued to a point where it is of much practical use. To produce data for two hypothetical transmission lines without any guidance on extending results is, I feel, the one weakness in the paper.

Data are given in Section 7 for two span lengths, and I have calculated curves similar to those of Fig. 7, confirming the authors' curves and also extending them to other span lengths, by using crest factors from Lewis (Reference 15 of the paper). The results are for all practical purposes identical to the authors' figures and extremely easy to obtain. (See Fig. C.) It is therefore not too difficult to build up one or two curves which would cover a wide range of transmission lines and which would begin to approach the usefulness of Harder and Clayton's method. Discrepancies occur in the assumptions made about the number of strokes to the line in a given period. In Section 2.4 the authors have given several of Dr. Golde's formulae for calculating the number of strokes to various types of lines, whereas the A.I.E.E. method is based on statistics and is intended to apply to the higher-voltage lines. An extension of the A.I.E.E. method by Clayton and Hileman makes some allowances for the height of the line when dealing with the smaller wood-pole lines.

There are, nevertheless, still wide differences between the two methods, and I have calculated the number of strokes to two arbitrarily chosen lines by three different methods and found differences up to about 3 to 1 in both the total number of strokes and in the ratio strokes-to-midspan/strokes-to-tower.

Whilst Figs. 7 and 8 give variations for different tower-footing resistances, no mention is made of the effect of counterpoise. It is usual to include the surge impedance of the counterpoise in the overall impedance to earth, so modifying the curves of Fig. C. At the end of Section 3 it is inferred that a single high earth wire would give the same protection as two lower earth wires, but the single high earth wire will have the higher surge impedance and could adversely influence the tower-top potential.

The paper sets no limit on the upper level of voltage which it is intended to cover, and there are two points applicable to high-voltage lines which are not mentioned and which appear to be worthy of inclusion. The first is the question of mid-span flashover. When transmission voltages approach the 300–400 kV

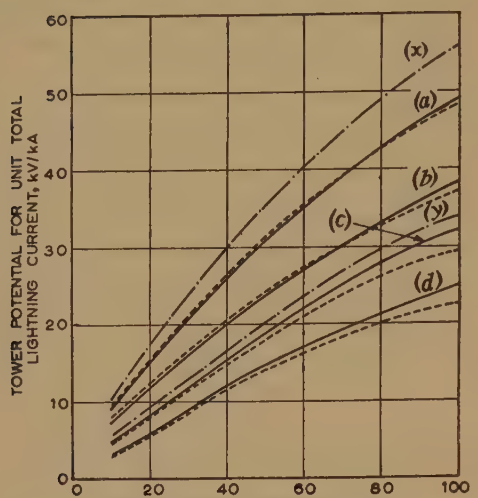

Fig. C.—Tower potential for unit total lightning current as a function of tower-footing resistance.

(*a*), (*b*), (*c*) and (*d*) refer to original curves of Fig. 7 of the paper, the solid lines being the authors' curves.
(*x*) Strokes to tower, 1 500 ft span.
(*y*) Strokes to mid-span, 1 500 ft span.

region the insulation at the tower is very nearly 'lightning-proof', but spans are usually long and with reasonable footing resistances strokes at mid-span would not usually cause flashover at the tower, but would be reflected and, owing to the long spans, conductor-to-earth-wire spacing becomes important.

On transmission lines a satisfactory compromise is usually not too difficult to obtain, but the protection of high-voltage substations from direct strokes by means of overhead earth conductors seems to be an occasion where this clearance should be kept in mind.

The other point which is giving some cause for concern is the high flashover rate experienced on certain 'tall tower' transmission lines in the United States.

Whilst these are as yet isolated cases it seems clear that a much more basic approach to the problem is necessary, and that not only will the surge impedance of the tower have to be taken into account more accurately, but also the voltage-time characteristic of the tower-top potential will have to be looked at more closely in relation to that of the insulation.

Dr. L. L. Alston: Reference is made in Section 5.13 to a proposal that a weighting of 10% be used, for flashover to occur across the insulator metal rather than between conductor and tower. In view of the large scatter of flashover voltages in non-uniform fields, it would be interesting to know whether this proposal has been tested in practice, and whether data are available on the proportion of flashovers which have occurred as intended.

I should also be interested in the authors' comments on the effect of corona in limiting internally generated surges, such as might be produced when an open-circuited line is switched out. According to the simplified classical analysis, the voltage builds up cumulatively in a series of steps, each of which is produced by a restrike at the circuit-breaker; ultimately a voltage may be reached which is many times greater than the peak operating voltage of the line. Now, the peak operating voltage of the line is roughly equal to the corona inception voltage, so that corona current flows when that voltage is exceeded. If that current is sufficiently large, the line may be discharged back to its peak operating voltage, during the time interval elapsing between two restrikes: in that case, the surge voltage would not exceed the value caused by the first restrike. This did in fact happen, in an experiment on a line model, but in this type of work results obtained on models are not conclusive and can only be used as very crude indications.

The corona inception voltage of a line is largely determined by the permissible power loss, but I wonder whether the authors might consider it worth while to attempt to design a line so that corona current increases very rapidly with increase in voltage beyond the inception value.

Dr. B. C. Robinson: In Section 7 the authors refer to the use of earth wires below the phase conductors. I should like to ask what is the advantage of putting the earth wires in this position rather than above the phase conductors. The two uses of these earth wires would appear to be a reduction of the effective tower earthing impedance and to support pilot wires from a catenary, as mentioned by a previous speaker. Against this is the loss in the direct surge protection as stated in the paper.

Lengths of span between poles of 885 ft and 442·5 ft have been used to evaluate curves in Figs. 7 and 8. These were chosen for mathematical convenience. Could the authors give an approximate value for the average span length on the British Grid and of the amount of variation to be anticipated except in special positions such as road and river crossings.

[The authors' reply to the above discussion will be found on the next page.]

SOUTH-WEST SCOTLAND SUB-CENTRE, AT GLASGOW, 30TH JANUARY, 1957

Mr. R. J. Rennie: According to figures now available it appears that the average isoceraunic level for this country during the four years 1951–55 was 8·2 and for the South of Scotland, 5·7. As the authors point out, this figure is at best a very rough guide to the incidence of lightning strokes to ground, since, to the inevitable human errors of omission and commission, are added the diverse and often unexpected effects of the most capricious of all natural phenomena. I venture to suggest that the Board's 11 kV system, which straggles for 5 054 tortuous miles over the 8 160 square miles of the South of Scotland, provides a better measure of the relative incidence of lightning strokes from year to year than the reported isoceraunic levels. For instance, in the years from 1948–49 to 1953–54 the faults due to lightning per 100 miles of 11 kV overhead line per annum varied from 4 to 27.

In Section 5.12 the authors direct attention to the merits of an all-insulated line using wood poles and unearthed ironwork. There are about 800 miles of 33 kV overhead line now in service in South Scotland about half of which is of unearthed construction. During the period between January, 1951, and December, 1956, 69 faults were recorded on the 33 kV system as being due to lightning, of which 44 caused no damage. Of the remainder, 18 resulted in damaged insulators and 7 in damage to conductors or jumpers. These figures can be classified as follows:

Lines of earthed construction.

Total number of faults due to lightning ..	56
Faults causing persistent damage	20

Lines of unearthed construction.

Total number of faults due to lightning ..	13
Faults causing persistent damage	3

In Section 6, the authors recommend over-running earth wires for at least a mile from the substation. Most of the 33 kV lines

of unearthed construction in this district have two over-running earth wires for half a mile from each substation and have surge diverters on the terminal poles. So far this practice appears to have been effective in preventing damage to substation equipment due to lightning surges, only two cases of damage to transformers having been reported during the 5-year period.

In Section 8 the authors point out that 80–90% of outages can be successfully reclosed, and that modern high-speed relays and circuit-breakers are effective in preventing damage due to the 'follow' arc. Development of automatic high-speed reclosing has tended to lag in this country owing probably to (*a*) the lower incidence of lightning, (*b*) the relative shortness of our overhead lines, (*c*) the relatively high proportion of interconnected feeders, and (*d*) the relatively high proportion of manned substations. In the U.S.S.R., where long radial feeders are the rule and not the exception, automatic reclosing of circuit-breakers controlling overhead lines of voltages up to and including 220 kV is standard practice. The Russian engineers claim that on their very extensive systems thousands of outages are avoided every year by this means.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. A. Morris Thomas and **D. F. Oakeshott** (*in reply*): It is useful to have the salutary reminder by Mr. Simpson that in designing a transmission line it is no less, and perhaps even more, important to ensure that a strong wind does not blow it down than that a lightning stroke does not cut off the supply. The very speculative nature of the one-third ratio suggested for strokes-to-earth frequency in tropical regions might well have been given more emphasis in the paper. Further reference to this is made later. As regards what is meant by 'tropical regions' we can only assume that the term denotes regions situated between approximately 23½° of latitude north and south of the equator in which the sun can be observed vertically overhead, in accordance with customary usage.

Theoretical procedure for predicting line performance can be put forward only tentatively, to be tested by experience. The theory, however, serves an important purpose in indicating the information which needs recording.

In the calculations for the curves given in Fig. 7, the tower inductances, effect of reflections, etc., are included; Mr. Simpson's expressions, used for illustrative purposes, greatly oversimplify the relationships. At present the uncertainty associated with the estimate of strokes-to-line frequency in any given case scarcely justifies a closer regard to accuracy in other respects, such as corrections for waveform, which Dr. Golde would like to see included. No doubt such refinements will be required in time to come.

We do not agree, in general, with Mr. Davis and Mr. Dixon that line insulation should be regarded more or less as a means of providing surge protection for station apparatus. The surge-protective devices at the station should be adequate for the purpose they serve, and choice of line insulation, other than perhaps for the mile of line adjacent to the station, will depend essentially on other factors, of which the chief is possible interruption of supply. The effect of a cable termination is referred to in the parent E.R.A. report.*

Dr. Forrest is quite correct in his comment on Fig. 1. We note with interest that a lower figure for strokes-to-earth than that suggested in the paper has been obtained by direct recording methods and that some confirmation of a non-linear relationship between this figure and the isoceraunic level exists. Nevertheless, as suggested in Section 2.4, an assumption of proportionality is probably advisable at this stage.

We agree with Dr. Golde's reference to the severity of the stress imposed by a steep-fronted surge. For this reason it is particularly important to obtain a low tower-footing resistance in the neighbourhood of a station in order to reduce the surge amplitude as far as possible.

In reply to Mr. York we think that, in the case described, it would probably be necessary to increase the interphase spacing to obtain improved performance, and this would be uneconomic.

The 0·85 figure for ratio of outages to flashovers is based on U.S. experience and may be lower according to circumstances.

* E.R.A. Report Ref. O/T14.

A reduction of one-tenth, such as is mentioned, would appear to warrant further investigation. In general the number of lightning incidents observed on the British system is not very different from that given by the formulae.

Mr. Cherry's reference to the I.E.C. standard insulation levels can be understood only if he is thinking of operation in polluted atmospheres, in which case special measures are, of course, required and are described in the paper. The question of clearances is controversial; we have given an authoritative suggestion but do not claim that expert opinion is wholly in agreement. All who have first-hand experience with high-speed auto-reclosing switchgear seem to agree that it is capable of giving substantial improvements in performance, but there is as yet insufficient recorded information upon which to base firm conclusions.

Two worked examples as suggested by Dr. Clark are given in the parent E.R.A. report. His procedure for prediction of line performance and choice of line insulation levels does not differ in principle from the one described in the paper. The dispersion curves given in Fig. 5 enable the 0% and 100% values to be estimated from the 50% value. No difficulty arises when a specified withstand value is applied in a proof test. The claim that long-rod insulators are better than the cap-and-pin type has not been by any means confirmed by tests at the C.E.A. Research Laboratory. Cap-and-pin insulators tend to produce radio interference only under bad conditions owing to sparking at contacts between corroded metal surfaces. Our figure for the time lapse between trials in impulse tests is authoritative and in our opinion is reasonable. The results obtained by Dr. Clark on the effect of rain on impulse flashover are valuable as this question is still, to some extent, in need of clarification.

In reply to Mr. Edwards, for power-frequency tests the A.S.T.M. correction factor humidity of 4 g/m^3 is 4% greater than our figure, and for 22 g/m^3 is 2% smaller, the differences are less at intermediate humidities. In impulse tests the differences do not exceed 1%. Our figures agree better and quite closely with the experimental results published by Fielder,* and Pfestorf and Strauss.† According to our Reference 21, the 50% value for a rod gap is subject to a coefficient of variation of approximately 2·5%, and this is stated to apply also to insulator flashover. As stated, the test conditions in general conform to British Standards apart from the U.S. values, but the differences are negligible.

We agree that the year-to-year variation in isoceraunic level could be taken into account if desired, as suggested by Mr. Atkins, and the variation could be subject to statistical analysis. We see no reason, however, for restricting the period to obtain the estimate of the mean isoceraunic level, as proposed by Mr. Green. Our method of illustrating the dispersion in flashover voltages has the merit of simplicity; the use of specially ruled

* Fielder, F. D.: *Electric Journal*, 1955, 32, p. 543.
† Pfestorf, G., and Strauss, K. H.: *Archiv für Elektrotechnik*, 35, 1941, p. 740.

probability paper is certainly sometimes useful. That induced surges are unimportant on systems above 33 kV is in accord with authoritative opinion and theoretical calculations. The difference in the resistance of the earth wires, to which reference is made by Mr. Nicholls, would have no significant effect. We are grateful for the additional information on insulator swing.

The importance of collection and analysis of service records from as many sources as possible, as mentioned by Mr. Stock, is recognized. Effort to this end is undertaken by the E.R.A., and it is hoped that our paper will assist in extending the scope of this work.

Mr. Sumner's account of his observations in Malaya is of interest and importance, and his projected report is likely to be a major contribution to the subject.

We agree in principle with Mr. Tompsett, but we confess our inability to rise to the heights of optimism implied by his final suggestion.

Mr. Atkins will find that his question on strokes-to-line frequency has been dealt with above; the authority for absence of power arc following insulator flashover is our Reference 8.

Mr. Csuros's point with regard to the effect of height of tower is dealt with in our reply to Mr. Simpson. The tower heights used for the curves in Fig. 8 are 80 ft and 60 ft for long and short spans, respectively. For other tower heights expressions given in Reference 5 may be used.

We are in agreement with Mr. Dixon apart from his first comments, to which reference is made in our reply to Mr. Davis.

It needs a textbook to cover adequately all possible cases as suggested by Mr. Wood, but we give appropriate references. It is nice to know that our calculations have been confirmed by an independent authority. We give data on the effective resistance of counterpoise in Section 4. A more accurate and detailed treatment may be necessary to solve the problems of the high flashover rate on 'tall tower lines'.

The proposal referred to by Dr. Alston has not, so far as we know, been confirmed in practice. Corona increases the coupling factor and so tends to reduce surge amplitude, but we are doubtful whether the deliberate increase of corona current without reduction of corona inception voltage and insulation level is feasible by any means known at present.

In reply to Dr. Robinson, the advantage, in addition to those mentioned, of an underrunning earth wire is that it increases the coupling factor and so reduces the amplitude of surges due both to direct strokes and to back flashover. The average span length on the 132 kV British system is 900 ft.

Mr. Rennie's service records are interesting and valuable. The lightning faults in the 11 kV system mentioned fall within the range of expectation on the U.S. basis of the relationship of strokes-to-line to isoceraunic level.

1.32:621.36:634/635

Paper No. 2272 U
Jan. 1957

ELECTRICITY IN MODERN COMMERCIAL HORTICULTURE

By C. A. CAMERON BROWN, B.Sc., Member, and A. W. GRAY, Associate.

'he paper was first received 1*st October, and in revised form* 29*th October*, 1956. *It was published in January*, 1957, *and was read before the* UTILIZATION SECTION 17*th January, the* NORTH-WESTERN UTILIZATION GROUP 12*th February, the* SOUTH-WEST SCOTLAND SUB-CENTRE 27*th February, and the* NORTH STAFFORDSHIRE SUB-CENTRE 6*th May*, 1957.)

SUMMARY

Over the past 10 years there has been a significant change in the ole of electricity in horticulture. From being largely an aid to the mateur gardener, rarely used by the commercial grower, electricity ow plays a substantial part in modern commercial horticulture. ome of the earlier expectations, based chiefly on the small-scale work, ave not developed as expected and hoped. *In situ* soil warming, for stance, has not taken its expected place in commercial horticulture, nd large-scale glasshouse installations are few and far between. n the other hand, the use of soil-warming equipment to provide ottom heat for propagation in frames and propagating cases has icreased substantially. Direct space heating by electricity was hardly xpected to play any significant part in commercial glasshouse work, ut through electrical auxiliaries alone has it been possible to develop arious modern methods of large-scale automatic heating using either oal or oil. Where the circumstances and scale of requirement do istify direct electrical space heating, emphasis is placed on the need or correct design, particularly in relation to a proper basic temerature. Probably the most prominent role of electricity in comercial horticulture has been in the provision of artificial lighting for lant growing in various ways; increase of plant development and its ontrol have both been successfully applied through the use of electric ght in ways and with means which are commercially successful. The evelopment of new wiring methods and equipment has aided the rovision of safe wiring installations in horticultural premises.

(1) INTRODUCTION

The passage of time and the march of technical progress and pplication have been markedly impressed on the authors by ertain public references to a paper presented eight years ago, vith which one of the present authors was associated.[1] These eferences by outside and presumably detached observers have mphasized the fact that, while this earlier paper is still regarded by many as authoritative, as indeed it was at that time, it is no onger a true picture of the place of electricity in horticultural practice, least of all in the commercial sphere.

In some respects the situation has deteriorated, more particularly in the disappointingly poor expansion of electrical soil-warming in its basic sense of warming ground soil in which plants are grown. On the other hand, while the indications given in the earlier paper that all-electric heating of commercial glasshouses was hardly a practical expectation have not been confounded, the use of electrical 'aids', not fully envisaged then, has, in fact, made the modern coal- or oil-fired glasshouse a substantial user of electricity. Again the use of electric light as a horticultural process was hardly mentioned earlier, and certainly not developed, whereas now it is an almost exact science, and in wide use. In common, too, with the rest of the country and other industries, the commercial grower is becoming more appreciative of the value of the 'electric arm', and the electric motor is being put to an ever-widening range of use from soil-shredding to automatic ventilation.

Above all, with the increasing pressure from both economic and scientific development, the modern grower is faced with even more exacting operational requirements, and he can no longer fully rely on human experience and judgment to satisfy them. In particular, he is faced with the need for close environmental control, and here, in particular, he is almost forced to recognize and utilize the automatic precision and discrimination uniquely afforded by electricity. Indeed, it is through electricity that 'automation' reaches horticulture.

While the authors, in presenting the paper, have in mind the commercial grower with his larger requirements, and the attraction both to manufacturers of equipment and to Electricity Boards and other supply authorities, they are far from being unaware of the total potential of the amateur gardener as a user of electricity and a purchaser of equipment. Generally, however, the treatment of commercial problems, as described here, can be directly applied to amateur requirements by simple and obvious scaling-down, and relevant comment is made where appropriate.

There is still no exact basis of determination of the potential field of consumption in commercial horticulture. All that can be gathered from the National Farm Survey[2] is that in England and Wales in 1943 there were 5200 market-garden holdings, with a further 2900 given a mixed classification under fruit, vegetable and hops, all being over 5 acres. Some of these may have some glass, the main outlet for electrical methods and consumption, but most will not. In addition to these, however, there are some 70000 holdings of less than 5 acres, and, by their very size and nature, many may well have small glasshouses and frames. That horticultural electrification has considerable potentialities as a consumer of energy is substantiated by two installations, one in the North-West and one in the South, each using some 250000 kWh annually.

The number of amateur gardeners is unassessable, but some idea of the number which take the trouble to show their advanced interest in good gardening is indicated by the membership of the Royal Horticultural Society at 50000; the combined circulation of the four leading gardening weeklies exceeds 500000 and it has been estimated that some two million people are members of some horticultural society or group. A reasonably equipped amateur installation of greenhouse and frame might be expected to use 4000–5000 kWh per annum.

(2) SOIL WARMING

The term 'soil warming' originated in the basic application of electrically heated wires or cables to the warming of soil *in situ* either in a glasshouse or in a frame under lights. It has, however, been used rather loosely, and with wider significance, in references to the use of such equipment for the raising or propagating of plants on special propagating beds or benches. Nevertheless, two quite distinct problems, both economically and technically, are presented by the two spheres of application.

(2.1) *In situ* Soil-Warming

The direct and simple application of the principle of soil-warming by electricity has unfortunately not fulfilled all the high hopes expressed for it in 1948, in so far as the application of soil-warming methods to the main ground, in either glasshouse or frame, has not progressed by more than a modest degree.

The authors are with the Central Electricity Authority.

In respect of the glasshouse, i.e. mainly for the tomato crop, it was expected that soil warming would fall into two stages:

(*a*) Pre-warming before planting in order to cut down to a day or two the otherwise necessary period of two or even three weeks of glasshouse space heating to warm the soil to planting temperature.
(*b*) Maintaining the proper root temperature in the soil towards enabling the general house temperature to be reduced, so economizing in space-heating costs.

The former effect (*a*) has not been disputed, but the latter (*b*) has not been accepted by the leading horticultural scientists, who have been unable to confirm in controlled trials that any such gain is realizable; nor indeed has the E.R.A. As to put the whole capital cost on the indisputably successful *pre*-warming might well cancel the value of the financial gain achieved there, it has been considered advisable to exercise caution in dealing with this field of development. Nevertheless, the authoritative findings, while indisputable under the circumstances of the investigations, do conflict with certain very satisfactory experiences with *maintenance* warming on holdings where the application has been in use for some time. It is therefore not unreasonable to conclude that the whole husbandry at both the John Innes Institution, where one of the authoritative investigations was made,[3] and the E.R.A. is of such a high order that soil warming becomes an attempt to 'paint the lily'. It may well be, therefore, that the answer to something approaching a conundrum is that some growers, probably many, cannot maintain such a high general standard and that soil warming has a 'hospital' value as a rescuer. Just when to recommend the application on these grounds presents a tricky problem.

The reason for the lack of wider use of the soil-warmed frame is more readily explained. One hard fact is that commercial growers in this country, in contrast to the Dutch and the French, are not frame-minded, and only an infinitesimal part of our horticultural products is produced in this way. The other, and possibly harder, fact is that, while soil warming undoubtedly produces earlier cropping, particularly of the staple frame-crop lettuce, the prices obtainable for the earlier-produced lettuces are rarely the highest. The real gain to the commercial grower in hotbed production is the possibility of a rapid turnover giving him as many as seven croppings from the same frame in the course of a year, as is common in Holland and France. That it is possible here, too, has been demonstrated as far north as Scotland, though before the electrical method was as advanced as it is now, and using other and less simple methods. The position is largely one of international economy, and, should we at any future date find it impossible to draw on these special Continental skills, the way may then be opened to a great extension of the use of electrically warmed hotbeds in our own country.

For the amateur gardener the reverse is true. He rarely possesses the skill to grow an early indoor tomato crop, and the application of soil warming for this purpose can hardly be regarded as other than a pleasant diversion. Any reasonably competent amateur gardener can, however, grow lettuces in frames, and the advantage of having early lettuces is well worth the modest cost of a small soil-warming installation. It has now been widely confirmed by amateur gardeners that the 'simplified hot-bed' method developed by the E.R.A.[4] is as nearly infallible as any growing procedure can be.

There is, too, the possibility of using soil warming in open ground, sometimes alleviated by the use of continuous cloches; this, however, is still in the stage of experimental investigation by the E.R.A.

(2.1.1) **Methods.**

For the commercial grower there can be little doubt that the extra-low-voltage transformer-fed bare wire is the only really safe proposition, the voltage used varying up to a maximum of 30 volts. The methods of laying and straining are largely those described in the earlier paper, a parallel-series arrangement of the galvanized steel wires enabling the main feed connections to be kept to one end of the house. Specific loadings vary from 5 to $7\cdot5$ watts/ft^2, depending on the required duty and the time available for application.

For the amateur grower, caution would still indicate the e.l.v. transformer-fed bare wires as the ideal, although the substantially lower cost of the l.v. (240-volt) cable must always be attractive to him; the availability of one type of l.v. cable with an earthed metallic screen and of another with a very substantial and tough plastic covering certainly improves the position. Nevertheless, the authors strongly recommend that for any use of soil warming where cultivation of the soil is necessary, the only safe form is the e.l.v. method.

It is appreciated that the e.l.v. method has also been applied by using either wire-netting grids or wire in spiral form. The former have been used experimentally in Holland, but serious defects, both electrical and mechanical, have shown themselves to such degree as to have redirected thought to the galvanized-wire method as used here. The spiral method offers obvious complications in both installation and subsequent cultivation.

(2.2) **Propagating Benches and Beds**

No qualifications or reservations apply to the other main sphere of applying soil warming, i.e. the provision of bottom heat for propagation, by seed-germination or by cuttings, and their subsequent growing-on, whether on benches in a glasshouse or in beds under lights. This has been found to meet a fundamental need—and weakness—in the previously established methods of propagation; these had mainly been carried out, commercially at least, in propagating houses, where large volumes of air were maintained at the temperature of 60°F or above required in only that small fraction of the space occupied by the boxes or pots containing the seeds or cuttings. Not only was this a costly process, but, when germination had taken place, the condition presented to the seedlings was far from the requisite for balanced growth, i.e. 'warm toes and cool head', which produces a sound and vigorous plant. Soil warming makes available the ideal condition of required temperature in pot or box while a modest and less costly overhead temperature is being maintained in the house generally.

The soil-warmed propagating bench is of particular value as a 'rescuer' in the case of a heated propagating house where there has been difficulty in maintaining the space temperature at anything near that required to produce germination temperature in the soil, and, in fact, a surprisingly high proportion of orthodox propagating houses are running far below the optimum temperature for the purpose.

At the same time, the facility with which the propagating bed in frames under lights can be protected at night by covers and mats gives more scope to this method of propagation than is generally realized. While obviously not the ideal place for the exotics, the propagating frame with a soil-warmed bottom, and without any other heating, can provide the most economical method for the mass production of the staple early-summer half-hardy bedding plants, with the precaution, at least in the early stages, of covering the glass at night.

(2.2.1) **Methods.**

While, for the larger scale of propagating bench or bed e.l.v. bare-wire grids are generally used, the l.v. cables are equally practicable; the l.v. cable is less expensive for the smaller loadings, and is of particular advantage if the pro

agating area is to be subdivided into separately switched sections.

To a specific loading of 5–7 watts/ft^2, the wire or cable is laid in a bed of sand, which must be kept moist to ensure proper heat-conduction. A frequent mistake is to lay the cable in peat or cinders, neither of which will conduct the heat adequately; the sand used should preferably be builder's sand, having a certain clay content which helps to hold the moisture in the sand bed. If seed boxes are used they must be bedded firmly on the sand and against each other; if pots are used the space between adjacent pots must be filled with peat to avoid cooler air circulating round the pots, but the bottoms of the pots again must be firmly on the sand.

The propagating temperature can be controlled by a stem-type thermostat with the rod inserted horizontally in the sand and just under the surface. As, however, with the specific loadings generally used, the temperature response is slow, it is not generally of advantage to use a thermostat. Hand control by observation is usually adequate, although a thermometer should always be used; a Simmerstat would be a more practicable device than a thermostat, and less costly. The case is rather different for the amateur who may be away from home all day; a rather higher specific loading and thermostat control may then be justified.

(2.3) Propagating Cases and Frames

The fullest control of propagating environment with minimum running cost is obtained by the use of either a propagating case or a propagating frame, and many of both are now being installed; the basic principle in both is an enclosed space of minimum height fitted with soil-warming equipment to give bottom heat, and space-heating equipment with thermostat to maintain the air space at the required temperature. The former consists of a glass-covered frame on a bench inside a glasshouse, and the latter is simply an outside frame covered by lights. In both, the soil warming is of the order of 6–7 watts/ft^2, the space heating being generally to 60° F in the case, and to 55° F in the frame where rather hardier subjects are handled (Section 2.2). Either e.l.v. or l.v. warming equipment may be used to provide bottom heat, and is controlled as for hot-beds.

(2.4) De-frosting of Sports Grounds

While hardly a horticultural application of electrical soil-warming, developments in this sphere might be linked with the possibility of using similar methods to prevent the freezing of football pitches, with the resultant loss of money to the clubs and entertainment to the spectators. Prevention rather than cure is envisaged, because the work of the Sports Turf Research Association,[5] which has demonstrated the practicability of the idea, tends to suggest that anticipation and prevention of freezing may well be a better proposition than actual de-freezing after the ground has been frozen.

Although the Association had established in 1951 that loadings of about 8 watts/ft^2 would be effective, no football pitch yet appears to be so equipped. Admittedly, a few early and promising inquiries were probably discouraged because estimates were then based on the e.l.v. system with its quite substantial initial costs. Now, however, there are available l.v. plastic-covered cables of tough construction, which would lend themselves to being laid by mole plough and should reduce considerably the cost of an installation.

The total loading for a full-size football pitch would be about 500 kW, which, properly handled, can be off-peak, with perhaps the possibility of a late run on a Saturday morning. Thus, in the worst event of a sustained frosty period, a nightly warming plus Saturday 'boost' would only expend some 40 000 kWh per week; at an off-peak charge of a penny per kilowatt-hour, this would cost about £150, a very modest fraction of the gate-money otherwise lost or reduced. The capital cost even at as high a figure as £5 000 would be nothing to the loss by damage to a first-class player who might be injured on a near-frozen ground.

There is, too, a further possible gain to the club in the subsequent re-seeding of worn parts of the pitch—the 'diamond'—which commonly has to be done each season and would go ahead more vigorously with the warm soil conditions aiding both germination of the seed and growth of the grasses.

(3) SPACE HEATING

In considering horticultural space-heating, the tendency is to think only in terms of heating glass-enclosed growing space. While undoubtedly such requirements are the major call on horticultural heat, modern developments are demanding the provision of heating in certain thermally-insulated buildings. There is, too, a call for heat in providing localized, and sometimes temporary, comfort conditions for the staff in packing and potting sheds, etc.

(3.1) Space Heating in Glasshouses

After labour, the largest single expenditure in commercial horticulture is on heating glasshouses, but it would be hardly realistic to regard this as a promising sphere for the sale of electricity through direct electrical heating. If it could be so regarded and developed it would indeed be a substantial source of revenue to Electricity Boards, equipment manufacturers and contractors. To maintain an inside temperature of 60° F against a minimum outside temperature of 20° F, an acre of tomato-growing glass would require some 1 100 kW of heating equipment, and, during a normal growing season, February to October inclusive, it would use some 1 200 000 kWh in the south of England and some 1 600 000 kWh in the colder parts of the north of England and Scotland.

This otherwise possibly attractive load could not, however, be kept off-peak, and, while the rising cost of coal makes the 'penny unit' not so unreasonable, the normal demand charge could not be entertained by the grower. As the larger nurseries tend to be concentrated in certain limited areas, any substantial demand for electrical space-heating would lead to problems of distribution and mains augmentation. There are, of course, certain cases of smaller-scale, and perhaps more specialized, propagating and growing where all-electric heating might well be justified.

There is, however, a very considerable scope for developing the use of electricity in a sphere where it is really indispensable, i.e. in operating the essential auxiliaries in applying new and improved methods of using coal and, increasingly, oil.

(3.1.1) Space-Heating Auxiliaries.

The rising costs of fuel and labour are at last forcing the commercial grower to give serious consideration to applying modern methods and procedures to his basic requirement—the provision of space heating. This is resulting in two distinct lines of electrical development and application: (*a*) the use of automatic blowers, and automatic stokers where solid fuel is still used, and (*b*) conversion to oil, which would not be practicable without electricity. There has been in the electrical industry a general tendency to regard anything less than full and direct space-heating by electricity as hardly worth considering as a revenue producer, and, this being generally unattainable, to lose interest in the field of space-heating for commercial horticulture. In fact, of course, this is far from realistic, because a proper installation of electrical auxiliaries can produce quite an appreciable revenue with *no serious demand problems.*

(3.1.1.1) *Electrical Auxiliaries with Coal-Firing.*

The use of a fully-automatic stoker will involve a motor of from $\frac{1}{3}$ to 6 h.p. as well as a forced-draught fan of up to 3 h.p. Owing, however, to the comparatively high initial cost, this type of equipment is rarely justifiable unless the nursery or holding is so organized that one central boiler-house can handle all the glasshouses or at least a substantial block of not less than half an acre.

While some of the newer glasshouse holdings have been planned and placed so that the centralized fully automatic stoker system can be used, the majority of holdings have 'just growed' and no such single central system is economically practicable. In any case, the majority of glass is in units too small to justify this system. The present answer to the problem of simplified firing in such cases is the solid-fuel fire with automatic *blowing* but hand-stoking at appropriate and convenient intervals, the ash-pit being sealed and the air blown into it passing up through the fire-bed. Certain earlier unsatisfactory results with this quite simple system have been demonstrably due to failure to ensure both that the air provided was matched to the requirements of the fire and that the correct types of fire-bars were fitted.

In either type of installation a master-thermostat—or 'airstat'—in a selected house will start blowers and stokers in the first case, or blowers alone in the latter more simple case, to liven up the fire and raise the water temperature. In addition there should also be a thermostat—or 'waterstat'—at an appropriate point in the water system to ensure that the water is not allowed to cool down to such a point that recovery, in response to the airstat, will be slow. Finally, in any but the simplest installations, there will be circulating pumps in the hot-water system.

Such modern solid-fuel systems can involve from 150 h.p. in stoker, blower and pump power in the larger installations to a 1 h.p. fan in the simplest cases. Consumptions can similarly vary from some 150 000 kWh to 1 500 kWh per season.

(3.1.1.2) *Electrical Auxiliaries with Oil-Firing.*

Practically all makes and types of boilers normally used in glasshouse space heating can be adapted to oil-firing, and an increasing number are being converted. The form and extent of electrification is decided by the type of oil used, this in turn being governed by the size of the heating installation. The very small holding will probably tend to use the lighter distillate oils which require comparatively simple electrical equipment but are dearer. The larger holding will be able to justify the rather more elaborate equipment necessary to enable the cheaper heavy residual oils to be used.

For using light distillate oil, electricity is involved quite simply in pumping the oil, providing compressed air for atomizing it, and starting the flame by means of high-voltage electrodes.

For dealing with the heavier residual oils, the equipment requirement depends on whether 220 sec medium oil or 960 sec heavy oil is to be used.*

The medium oil remains fluid down to 40° F, and if kept in tanks in the boiler house there is generally no need for further heating at this stage. Where, however, the tanks stand in the open or in an unheated building, it is usually necessary to fit thermostatically controlled 3 kW immersion heaters, and thermal insulation is, of course, an advantage. The oil must eventually be raised to 170° F at the atomizing head, and, to ensure this, the oil is pumped from the main storage tank to a preheater tank fitted with a thermostatically controlled immersion heater, and thence to the burner. The loading of the immersion heater in the preheater varies with the rated oil consumption of the burners from 500 W for 3 g.p.h. (300 000 B.Th.U/h) to $1\frac{1}{2}$ kW for 9 g.p.h. (1 000 000 B.Th.U/h). The oil pump and an air-compressor, driven by a common 2 h.p. motor, feed oil and air to the burner, where the vapour mixture is ignited by an 11 000-volt arc provided from a step-up transformer.

The heavy oil needs more substantial electrical provision. It must first of all be kept fluid at 90–100° F, and no matter how sheltered the placing of the tanks, or how efficient the degree of thermal insulation provided, some heating is always necessary. Where, as is common practice, the bulk of the oil is kept warm by a steam or hot-water coil, a 3 kW electric heater is used to provide concentrated heating at the outlet; where, however, electricity is used for the bulk heating, special types of immersion heaters providing 12 kW or more are fitted. The oil must also be kept fluid on its way to the burners, and, while good lagging of all pipes is sometimes sufficient, it is often necessary to wrap the pipes with mains-voltage soil-warming cable under the lagging, so as to give from 7 to 10 watts per foot of pipe run. A further 3–9 kW of immersion heating is required in the pre-heating tank at the burner head to raise the oil to 220° F; again an 11 000-volt igniting arc is provided through a transformer.

Without elaboration, it is sufficient, towards realizing just how important is electricity in these spheres of application, to know that in a heavy-oil heating installation the meeting of the various requirements, some, of course, precautionary but essential towards confident and safe operation, calls for 14 electrical operations: bulk-heating, flow-heating, pumping, preheating, air-compressing or blowing, re-circulation, ignition, 'no-flame' control, re-cycling and lock-out, airstat, low- and high-temperature waterstats and alarm bell.

Fully equipped installations of 70 kW connected load are using up to 70 000 kWh per annum on oil-firing auxiliaries and water circulation.

(3.1.2) **Direct Electrical Heating.**

In certain circumstances and conditions it is practicable to make direct use of electricity in heating glasshouses. In commercial horticulture there are many small but highly specialized growers whose glass requirements are modest but whose standards of production—and relative incomes—are high. Such a grower can often afford the admittedly extra cost of direct electrical heating. (With him might well be considered the amateur who is even more highly advantaged by the use of electricity.) Such a grower, too, is unlikely to work on a scale justifying the installation of fully-automatic oil equipment yet may regard it as essential to be freed from frequent calls on his time to attend to solid-fuel boilers. If the industry 'wants' this greenhouse load, or, more correctly, consumption, it has refrained, somewhat surprisingly, from really hammering home to the smaller grower how electricity could free him from very trying calls on his time.

(3.1.2.1) *Equipment.*

There is little, if anything, new to report on equipment for heating smaller glasshouses and amateur greenhouses. Where tubular heaters are specified, only those of approved horticultural type should be used. The use of low-voltage uninsulated strips or tubes is highly practicable but involves a higher initial cost. Where a conversion from a water-heating system is involved, use can be made of a 'conversion set' which enables an electric boiler to replace the solid-fuel boiler. At the same time, suitable 3 kW heaters are available in various forms for insertion singly or in multiples in the heating pipes themselves or, alternatively, in an end tank replacing the boiler, but always *inside the house proper*. It is rarely advisable, even if possible, to fit the heaters to the solid-fuel boiler itself, since this is generally outside the house to be heated. Fan-unit heaters offer simplicity in installation, but there may be some damage to tall-growing crops if the

* The measure of fluidity of oil is taken as the time in seconds to flow through a specified aperture when at 100° F.

arm air impinges closely on them; the use of the fan alone may of considerable advantage in houses where the natural ntilation is deficient.

.1.2.2) *Design.*

Electricity is not, perhaps, alone in suffering in effect and putation from poor design of the installation, but has certainly od grounds for asking to be 'saved from its friends' so far as asshouse heating is concerned. The troubles experienced in ectrical heating have taken two forms: (*a*) unexpectedly high nning costs, and (*b*) failure to maintain temperature under ry cold conditions. The authors regard the conditions relating these two points to be so serious and fundamental to satis- ction or otherwise in electrical operation as to justify some nphasis.

High running cost over a period is generally due to oversetting ne thermostat. The significance of 'target temperature' cannot e over-emphasized, and in this context Table 1 shows the

Table 1

STIMATED CONSUMPTION FOR PROPAGATING HOUSE 100 FT LONG × 10 FT WIDE. 2 FT 6 IN OF 9 IN BRICKWORK—5 FT TO EAVES AND 8 FT 6 IN TO RIDGE

Month	kWh with target temperature of:					
	35° F	40° F	45° F	50° F	55° F	60° F
January ..	458	1 536	3 378	5 638	8 457	11 322
February ..	664	1 673	3 392	5 661	8 710	10 726
March ..	390	1 192	2 682	4 882	7 518	10 176
April ..	—	181	894	2 452	4 676	7 248

robable consumption for the principal monthly periods for heating a propagating house of 100 × 10 ft to different target emperatures and in an average year. These figures are derived rom Grierson's work,[6] but differ from earlier estimates because experience has shown that, due to 'sun gain' inside the glasshouse, only 80% of the basic degree-days need be taken into account.

The authors consider that for winter maintenance, where there may be dormant plants requiring little more than protection against frost, a setting of 45° F should not be exceeded and often something rather less, say 42° F, should be ample. The thermostat may be set up when active spring work is started, but, even then, a setting of 55° F need only rarely be exceeded where special, and quite advanced, horticultural work is required. Indeed, the raising of the setting even to 55° F can be delayed for weeks if the benches are fitted with soil-warming cables. Still further delay in setting the main thermostat can be enjoyed if propagating *cases* (Section 2.3) are installed. There are so many considerations to be gone into carefully when giving advice on the electrification of a greenhouse that one cannot but be appalled at the 'slap-happy' way in which electrical installations are sometimes suggested to grower and gardener. Possibly, however, the most common cause of unexpectedly high consumption is the use of the wrong, and insensitive, type of thermostat. In *any space-heating* connection an approved rod-type thermostat with waterproof head is essential.

Failure to maintain temperature, assuming no breakdown of either supply or equipment, is due to insufficient heating load being provided. Often, of course, this results from sheer guess-work and over-the-counter purchase of a proprietary heater advertised in vague—if not, indeed, quite misleading—terms of performance. Sometimes, however, it results from otherwise conscientious calculation of load requirement from a basic temperature of 32° F. This, no doubt, is a relic from a long-established architectural fallacy, from which all branches of electrical heating installation have suffered, but the effect is more quickly felt—and most disastrously—in the greenhouse. The authors recommend that the basic temperature for glasshouse-heating calculation should be taken as *no higher than* 20° *F.* The intention of using a small greenhouse only after, say, March might justify the use of a higher basic temperature, but this is a somewhat dangerous move, since, not only are cold snaps in April possible, but almost certainly the grower will sooner or later be tempted to extend his range of growing by an earlier start, and his taking of this risk may well prove to be disastrous.

In this connection it is well to appreciate that the new standard recommendation of 29° F as a basic design temperature[7] refers to buildings of normal construction and of high thermal capacity; this figure would result in disaster if applied to glasshouses, where the basic temperature of 20° F should not be exceeded in calculating the heating requirements.

(3.2) Cases and Frames

The application of space heating to propagating cases and frames (Section 2.3) is most readily carried out with mains-voltage cable either plastic-covered or metal-sheathed and mineral-insulated. The loading for the space heating in the case can be simply calculated on a basis of 0·75 watt per deg F temperature lift per square foot of glass area; for the outside frame the calculation can be based on 1 watt per deg F lift per square foot. As with all space heating the thermostat should be of approved rod-type with waterproof head.

Electrical space-heating can be similarly used with advantage to provide frost protection in outside frames for the overwintering of the more hardy plants. This would utilize frames which would otherwise stand empty during the winter months, cut down the heating costs for the particular crop, and free heated glasshouses for the raising of less hardy crops.

(3.3) Thermally Insulated Buildings

There is considerable modern development in certain special processes which can be carried out in buildings which, while not necessarily thermally insulated, are of such substantial construction that the heat loss is low. This justifies the use of electrical heating, which in any case is operationally the most expedient. In some processes controlled lighting is an important factor; these are dealt with in Section 4.

The main special processes calling for heating only are the pre-warming of bulbs for early forcing and the growing of mushrooms in beds, in trays or on shelves. For the pre-warming of bulbs, temperatures up to 75° F are required, but since this is a late-summer and early-autumn application there are no peak-load difficulties. The main value of electricity in mushroom-growing, where a temperature of 60° F is sufficient, is that by using fan-unit heaters not only heating but also, just as important, internal air movement is provided.

(4) LIGHTING

Electric light offers an unmatchable tool to the grower who has need for artificial light, and the use of electric light in various forms and to different ends has been one of the most interesting and active developments of recent years. Most of this attention has, however, been given to the use of electric light in 'process lighting,' where the light has a direct effect on plant growth and control. Much less attention has been paid to the use of 'working lighting,' where electric light can revolutionize the working programme, particularly during the season of short daylight.

(4.1) Process Lighting

It has long been realized that light is a major factor controlling plant growth, but it was not until the development of suitable electrical light sources that controlled conditions could be provided under which to study this complex subject. Much remains to be done, but it has already been established that the effect of light on plant growth is threefold:

(*a*) The intensity of light controls the rate of plant growth, i.e. the bulk increase of stem and leaf.
(*b*) The colour of the light controls the shape of the plant, i.e. whether it is elongated or compact.
(*c*) The duration of light, i.e. the number of hours of continuous light each day, even at quite low intensities, controls the development of the plant towards maturity and the production of flowers and fruit.

From this three established techniques have been developed which the commercial grower has at his command:

(i) *Supplementary lighting* to augment natural daylight, so increasing plant growth during the winter months when natural daylight is much reduced.
(ii) *Extended lighting* to increase the hours of continuous light each day, so controlling the development of the plant towards maturity.
(iii) *Replacement lighting* in place of natural daylight so that plants can be grown to maturity in thermally insulated and dark buildings.

(4.1.1) Supplementary Lighting.

The main application of supplementary lighting is for the raising of early tomato and cucumber seedlings. The John Innes Institution[8] established that, by using 400-watt high-pressure mercury-vapour lamps, plants are produced ready for planting some two weeks sooner than would be the case under natural light conditions. Treated plants crop some two weeks earlier, giving a heavier yield of early fruit as well as an increase in total crop.

There are two methods of applying h.p.m.v. lighting, using either the 'single-batch' or the 'double-batch' methods. In the single-batch method the lamps are fixed in position over the propagating bench and by a daily irradiation of 17 hours the plants are ready in 17 days. The later development of the double-batch system afforded considerable economy in initial cost, and reduction of load, by suspending the lamps from an overhead runway. This enables each lamp to give *two* batches of seedlings a daily irradiation of 12 hours, resulting in a seedling for planting after 21 days' irradiation. The single-batch method is simpler in installation and handling, but the double-batch system offers no real difficulty, and is at least as widely used as the other. A recent installation of the double-batch system in Guernsey—the home of intensive tomato-growing—handles the largest output of irradiated seedlings so far known. The double-batch method offers the substantial electro-economic advantage of handling nearly double the quantity of plants for the same number of lamps, with the same maximum demand and for approximately the same consumption of electricity per 100 plants.

(4.1.2) Extended Lighting.

The flowering of the majority of plants is controlled by the length of day, i.e. the number of hours of continuous daylight; by the judicious use of shading to cut down the hours of continuous daylight, and by using artificial light to increase the hours of continuous light, it is possible to control the time of flowering of a wide range of plants. Much experimental work is being done to find ways and means whereby this response of plants to daylength control can be used to advantage by commercial growers. Up to the present, however, only two major techniques have been developed, each concerning chrysanthemums.

The first of these applications is the delaying of the flowering of chrysanthemums. Work at Reading University[9] has shown that, by increasing the hours of light at the time of bud-formation in late summer, the flowering of mid-season variety chrysanthemums can be delayed by as much as 30 days, thus lengthening the period over which the flowers of these varieties are available. This method of control has not so far been widely used.

The second application, one which is attracting more attention from growers, is the technique widely practised in Canada and the U.S.A.[10,11] of flowering chrysanthemums throughout the year by controlling the daylength, by extending the hours of light, or by shading. Precise schedules of lighting and shading have been worked out for selected varieties, and the success of the application depends on a rigid adherence to those schedules. Already a number of successful installations are in use in the country and the practice will undoubtedly spread. The largest installation so far recorded used 52 kW of lighting for a consumption of 37 500 kWh in its first year, which has since been increased to 220 kW, all being used off-peak.

(4.1.3) Replacement Lighting.

It is possible to grow quite a wide range of plants solely by artificial light, but the only application which has found favour with commercial growers is the forcing of bulb flowers. Using thermally insulated buildings and artificial light from tungsten lamps, the flowering of bulbs can be accelerated by as much as 10 days, as compared with bulbs flowered in glasshouses, with, of course, considerable saving in heating costs.

Bulbs which have previously been pre-cooled in electrically heated and refrigerated stores are brought at the appropriate time into the forcing sheds at a temperature of 60–70° F and given 12 hours' lighting per day from tungsten lamps suspended approximately three feet above the boxes and spaced so as to give a loading of 100 watts per square yard of forcing area. Heating and ventilating are usually provided electrically, both being thermostatically controlled; the lighting is controlled by time switch. A further economy in heating costs can be effected by using several tiers of forcing shelves in the same building, each shelf having its own lighting. Forcing sheds having three rows of shelves have been used with great success.

An allied application, although not strictly horticultural, which has found favour with quite a number of farmers, is the use of fluorescent lighting in conjunction with electrical heating and ventilating to control the rate of growth and type of sprout produced on seed potatoes, a technique based on work carried out in Holland[12] and modified to suit our conditions. Using thermostatically-controlled fan-unit heaters for heating and ventilating the stores, and fluorescent lighting for controlling the rate of growth, greening and type of sprout produced, seed potatoes can now be stored and sprouted in thermally insulated buildings instead of glass 'chitting' houses as has been the general practice. This not only results in saving on capital and running costs, but also produces a more consistent batch of evenly sprouted seed than is possible with the traditional methods, and gives an appreciable gain in early yield.

(4.2) Working Lighting

This really calls for little comment as the outlet for artificial lighting in adequate quantities is generally fairly obvious, e.g. in propagating houses, potting sheds, packing sheds and even glasshouses, where much work can be facilitated if lighting is provided. It might be well, however, to draw attention to the more neglected use of open-air floodlighting to enable outdoor work to be carried on in yards, loading bays, etc., after daylight has gone.

Table 2

TIME AND TEMPERATURE COMBINATIONS FOR HOT-WATER TREATMENT

Crop	Pest or disease	Temperature °F	Time	Remarks
Narcissus bulbs	Eelworm Bulb Fly	110 110	3 h 1 h	Maximum treatment 3 h
Chrysanthemum stools	Eelworm	115 or 110	5 min 30 min	115° F at 5 min is most commonly used
Strawberry runners	Eelworm	115 or 110	10 min 20 min	
Mint runners	Mint Rust (Puccinia Menthae)	115	10 min	
Brassicas seed	Black Leg (Phoma Lingam)	122	25 min	Seed placed in open-weave linen bags for immersion
Celery seed	Leaf Spot (Septoria)	122	25 min	
Cauliflower seed (summer)	Alternaria Brassiciola	122	18 min	

(5) SOIL STERILIZATION

The convenience and economy in labour of the electrical method of soil sterilization (more properly, partial sterilization or 'pasteurization') is appealing, though slowly, to commercial growers. The electrode type of electric sterilizer is still in use, and indeed a new make has recently come on the market. At the same time it is of interest to note that the E.R.A. contact-heating sterilizer—on the water-heating analogy affording immersion heating in contrast to electrode heating—referred to in prototype form in the previous paper is now available in modified form as a manufactured line and in two sizes giving capacities of 1 bushel (1·28 ft^3) and 0·25 yd^3 (nominally 1 cwt and 5 cwt). The earlier fears that the overheating of the soil nearest the heating plates would be detrimental have been found to be without foundation.

A certain degree of reluctance on the part of the grower to adopt the electrical method is largely due to an impression that only small quantities of soil can be handled; in fact, the simplicity of the electrical method, with proper planning, enables large quantities of soil to be dealt with. In particular, since the design of the larger immersion sterilizer of nominal 5 cwt capacity lends itself to simple filling and emptying, this apparently small appliance can be used to handle large amounts of soil. Apart from growers meeting their own requirements, several wholesale merchants are using electrical sterilizers of a 0·25 yd^3 (nominally 5 cwt) capacity to satisfy the substantial demands of their commercial and amateur customers. The consumption for electrical sterilization in either form is of the order of 3 kWh per hundredweight of soil sterilized.

(6) DISINFESTATION

An important problem in horticulture is the combating of pests and diseases of one kind or another, and the improvement in plant variety and in growing techniques appears to be accompanied by ever-increasing troubles from such sources. The problem can be regarded broadly as concerning those troubles which have to be met before planting and sowing take place, and those which occur during the growth of the plant. Electricity has some part to play at both stages.

(6.1) Pre-Planting

In certain types of plants, bulbs and seeds, the carry-over of pests and diseases from one crop to the next can be prevented by applying a warm-water treatment. This involves the immersion of bulbs, seeds, cuttings or runners in a bath of warm water for the proper time and at the proper temperature. Time and temperature combinations have been worked out for a range of subjects, and some of these are given in Table 2. The times and temperatures are critical; by increasing either or both, irreparable damage may well be done to the subject being treated, while with decreased time or lowered temperature the treatment would be ineffective.

The temperature is particularly critical as this is often very near that which would destroy the life of the subject; consequently really efficient control of temperature in the warm water bath is essential. Thermostatically-controlled electric immersion-heaters are the most effective means of providing closely controlled water temperature, and, for the larger baths, electrically driven pumps are used to circulate the water at a comparatively high rate to prevent stratification in the bath. For large-scale bulb treatment, electrically operated hoists can be used for lowering and raising the wire baskets containing the bulbs into and out of the bath.

(6.2) During Growth

For controlling pests and diseases on plants during growth the general practice has been to disperse insecticides and fungicides throughout the glasshouse by means of smokes and sprays. These measures are, however, temporary in effect and have to be repeated at frequent intervals. A more satisfactory procedure is the use of solid insecticides and fungicides, carried in an electrically heated container of some 25–50-watt loading, and liquefied and dispersed continuously throughout the glasshouse in the form of an aerosol mist of much smaller particle size than can be obtained with the alternative methods. The mist spreads throughout the glasshouse, covering structure and plants with a fine film, thus giving protection at all stages of growth and providing a much greater measure of control, with a considerable saving in labour and costs. Insecticides and fungicides covering a wide range of pests and diseases are available in cups containing quantities sufficient for approximately six weeks' treatment.

(7) POWER APPLICATIONS

In horticulture the main expenditure of energy, either natural or artificial, is in warmth and light for growing. There are, however, several ways in which the electric motor can play an important part. Probably the most important, and certainly a vital role, is that of the motor in the motorization of glasshouse heating already described. Pumping of water, however, is of increasing importance, not only for glasshouse and other limited watering, but also for large-scale outdoor watering and irrigation of horticultural crops and, on a field scale, grass and sugar-beet.

The commercial grower now has a number of uses for electric power in this ever-progressing mechanization. Soil-block making machines of 0·5 h.p. are eliminating the overheads and complications of handling clay pots, but, where these remain, power-driven potwashers are used. In the packing sheds, conveyor belts and grading machines facilitate the handling and packing of tomatoes, apples, pears, etc. When such crops as carrots, leeks, beet and celery are being handled, pumps are required for the washing machines involved, which are themselves power-driven. An increasing use is being made of power-driven soil-shredders of up to 3 h.p. and mixing machines of up to 2 h.p. in the preparation of soil composts.

While electric power is beginning to offer cultivating tools for the amateur gardener, there is still no serious sign of any electrical cultivation in commercial horticulture. The difficulty rests, as ever, in the handling of the unavoidable cable to the moving machine, and, unless the E.R.A. or some other source puts forward some acceptable technique, it is unlikely that electricity will make any headway in this direction. The nurseryman who cares to offer a presentable frontage to his visitors can find the electrical hedge-trimmer invaluable. The conditions presented on the larger holdings would seem to be well suited to the use of battery-operated trucks, and some indeed are in use.

While some reference must be made to the use of refrigeration in commercial horticulture, the main report must be of disappointingly little application. Undoubtedly some use is made of refrigeration processes which enable growers to store scarce and valuable seed for years, if necessary, and to treat bulbs, corms and certain plants, e.g. lily-of-the-valley, prior to forcing. For cold storage in bulk, little use has been made of mechanical refrigeration by the horticulturist, as distinct from the fruit grower, who is accustomed to cold-storing apples and pears in bulk for long periods. The commercial grower may use cool stores for holding certain crops, including flowers, for short periods before marketing, but he rarely, if ever, goes in for long-term storage on, for instance, the ‘deep-freeze’ principle. This is quite understandable because success in large-scale commercial growing depends on intensive specialization on one or two crops, without the diversity which more favourably could exploit deep-freeze holding plant.

One of the trickiest operations in glasshouse management is the control of ventilation, and the motorization of ventilators under thermostatic control offers the closest approach to complete automatic control. That it is not completely automatic rests on the need for human discrimination as to which direction the wind takes and the transfer of the automatic control to the lee side. That even such discrimination is within the scope of automatic control, and ultimately applicable as such, is most likely, but certain practical difficulties have not as yet been overcome.

The nearest known approach to a fully automatic greenhouse is one of 19 × 10 ft fitted with a 12 in extractor fan, which has been run on entirely automatic ventilation, combined with electric heating, for over a year. Tests have shown that, even with ventilators and door shut, up to 33 air changes per hour were achieved by the fan. During this period, crops of lettuce, tomatoes, chrysanthemums and a wide range of pot plants have been grown in the house, and results have been most satisfactory, so much so as to suggest that the climate in this greenhouse is superior to that in an adjacent greenhouse, growing similar crops, where the control of the air condition has been by manual control of ventilators, door openings, etc.

(8) WIRING

It is, of course, obvious that the wiring installation providing the various electrical services in modern horticulture may have to be capable of standing up to quite onerous conditions. In some places there will be bright light and even direct sunlight; temperatures in boiler rooms and often in glasshouses will be quite high; there will be, in the growing spaces, chemical sprays and dusts of various kinds, and, almost everywhere, high humidities ranging up to sheer watering. In many places, too, there is the risk of mechanical damage, if only from the periodical cleanings and scrubbings that are carried out to dislodge adhering and secreted dirt and spores.

While, therefore, the last consideration might indicate as advisable a system in galvanized conduit, the authors advise against this method, in view of the other chemical and condensation hazards envisaged. If, however, the conduit method is preferred, it may be more safely employed in the plastic form. By and large, however, there is much to be said for preferring a composite cable system, and effecting mechanical protection by careful placing, or by local mechanical protection by conduit where impact is unavoidable. Of the composite systems available, the simple rubber-sheathed type would not, of course, be satisfactory in the glass-covered spaces; the braided covering of the ‘farm-wiring’ type would meet the conditions of high sunlight, but the roughness of the braiding might offer difficulty in the dislodging of bacteria or spores. While a protective coating of white paint would make the rubber-covered cable more suitable, it would seem to be better to use one of the smooth-surfaced p.v.c.-covered cables, and there is no evidence that these fail to stand up to glasshouse conditions. For lighting outside yards and packing sheds the grid-suspension system is excellent; it has been used in glasshouses, but these are rarely structurally suited to take the end strains involved.

The mechanical advantages inherent in the metal-sheathed mineral-insulated (m.s.m.i.) wiring system must give it a high order of consideration for horticultural installations, but a deterrent factor has been the possible corrosive effect on the metal sheath of the various smokes and sprays likely to be used. While some of this doubt is being dispelled by successful and apparently trouble-free use of m.s.m.i. cables in propagating cases and frames, these have been in use for too short a time to assess the chemical danger. In any case, however, the problem would appear to be solved by the development of m.s.m.i. cable with an overall plastic sheath, which is claimed to be impervious to attack from any of the chemicals likely to be encountered. It may well be that, despite its higher cost, the plastic-covered m.s.m.i. cable is the best solution to the problem of wiring horticultural premises in general and glasshouses and frames in particular.

The use of watertight control gear, switches and socket-outlets inside glasshouses, frames and other damp situations is, of course, essential. Sometimes the conditions can be eased by having the control in another place, e.g. the main switching for a bank of hot-beds can be inside any convenient and dry shed nearby. While, in principle, socket-outlets should be avoided so far as possible inside glass structures, there are circumstances where their use is unavoidable, e.g. where mains-voltage soil-warming cables are used in propagating benches and beds and may have to be removed occasionally for rearrangement or even regularly if the space is later required for growing on. Safety in this procedure is facilitated with economy by the use of a type of moulded-rubber socket-outlet, with captive watertight cap, and with the corresponding plug also of moulded rubber and waterproof; the extension of the range to include a 2 amp size, as well as the 5 and 15 amp types, is a great boon in these applications.

(9) CONCLUSIONS AND ACKNOWLEDGMENTS

It is hoped that a sufficient picture has been given to indicate that a significant and substantial change has taken place in the

'climate' of horticultural electrication during the past eight years or so, and that electricity, once perhaps largely regarded as more properly the preserve of the better class of amateur, is now an everyday tool to the commercial grower. There is, too, the suggestion that the consumers' engineer, with a horticultural holding in his domain, need no longer regard this as hardly worth his attention, but as a potential consumer of electricity on a scale not envisaged even a few years ago.

Not only has the outlook changed in regard to growing, but also in research and experiment. While this country has probably been the leader in soil-warming developments, most of the basic work in light and lighting is still being done in Holland and America, although most western countries and, of course, Russia, are expanding their work on this subject. The E.R.A. is taking the leading part in applied research here, and its present work on light sources, and on light bands in particular, may well lead to quite impressive developments and applications. One would expect such work from an electrical organization, but other institutions have carried out, and are carrying out, very useful work on the electrical side, if sometimes only on the fringe. The National Institute of Agricultural Engineering at Silsoe is working on the measurement and integration of radiation from solar and artificial light sources; the National Vegetable Research Station at Wellesbourne uses electrical methods widely as handmaidens to its basic work; the Ministry of Agriculture's Horticultural Stations are developing field techniques involving soil-warming, lighting of growing plants, etc. In the sphere of pure research Reading University is working on light development within well-defined bands. Last, but not least, mention must be made of the John Innes Institution, now at Bayfordbury, which put the process of light irradiation of young seedlings on a practical basis in the United Kingdom.

While the authors cannot hope to refer to all the sources of information on which this paper was based, they would like to mention, in particular, Professor R. H. Stoughton and Dr. Daphne Vince of Reading University, Mr. E. W. Golding and Mr. A. E. Canham of the E.R.A., Mr. J. C. Lawrence and Mr. A. Calvert of the John Innes Institution, and Drs. J. Philp and W. G. Keyworth of the National Vegetable Research Station, who have all dealt patiently with queries on the scientific and research side. On the field side, the authors owe much to all their colleagues on the staffs of Area Boards, who have helped to put electro-horticulture into successful commercial operation, and, in particular connection with the preparation of this paper, to Messrs. Martin Harvey, R. H. Marshall, L. Jenner, G. Print, W. L. Cox, and E. C. Claydon. On the manufacturing side they are particularly indebted to Messrs. C. Fawcett and H. G. Pemberton.

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DISCUSSION BEFORE THE UTILIZATION SECTION, 17TH JANUARY, 1957

Mr. A. Graham Sparkes: I should like to say one or two words on behalf of the grower. I feel that the authors' remarks concerning the use of mercury-vapour lamps on tomatoes in the Worthing area as compared with that in the Channel Islands are a little unwarranted: the light conditions in the Channel Islands would presumably be better.

On a visit to the United States four years ago, my father was impressed by the fact that growers there were able to produce chrysanthemum plants out of season, by the use of electric lights and shading cloth. When he returned, he ordered 40 000 plants from the United States, at the same time installing six hundred 100-watt lights in a half-acre block of glasshouses. Since then we have acquired nearly 2 000 lights in two acres of houses, part of which glass area is stock.

I should like to point out that some support from the electricity industry's side in experimenting would aid the grower a great deal. There is a great amount of expense and time involved in growing plants under new conditions and with new methods, and since that is coupled with the growers' lack of knowledge of electricity and its uses, it would be much appreciated if we could get together more often and discuss the tremendous possibilities yet to be discovered.

Reference is made in the paper to daylength and its extension by the use of electric light. It is slightly misleading in that we are not increasing the daylength so much as breaking up the length of the night, by bringing in lights and using them during the night. The maximum permitted load at the moment is only 64 kW, owing to the limitation of inadequate mains service. It is difficult to stagger the load which has to be broken up without giving a night of more than 9½ hours. I therefore had no alternative but to alter my planting schedules, and this produced plants which initiated bud before they were tall enough to be worn as buttonholes. This example gives some idea of the troubles one can have with plants themselves under artificial conditions, apart from trouble with the supply of electricity. With regard to the propagating of the chrysanthemums, I installed soil heating whereby the chrysanthemum cuttings are rooted in fine grit. It was hoped that it would speed up the

process of rooting, which it has done; but I also desire to install some automatic means of mist propagation to increase the rapidity with which the plants root. If they can be given more sunlight without increased transpiration by keeping up the moisture content of the plant throughout by artificial means, it is possible to turn out more plants in less time, and I feel that electricity will really help me in that way.

As far as carnations are concerned, there is an increasing demand at the present time in my propagating department, and whereas in the early days it was necessary to go to great lengths to prepare carnation cuttings with a knife, which was a disease spreader, and then to wait for the cuttings to take root, it is now possible with soil heating and more efficient temperature control to put in the cuttings without preparation at all, and to promote a very rapid growth of roots.

The question of ventilation and air-conditioning is interesting, and there again the United States are ahead, probably because they have more acute climatic conditions than we have. I feel that air-conditioning through the medium of electricity will enable us to control temperature at a much greater average level, so that we can obtain better quality and bloom consistency throughout in the process of growing.

We in the horticultural field are looking forward to very rapid developments in the near future. I feel that for too long we have been with our feet in the air, and perhaps not sufficient support has been given to this remarkable industry with all its possibilities.

I am very glad that Mr. Cameron Brown and Mr. Gray in presenting the paper are really pushing things forward to enable us to produce our crops more easily with better quality, leaving expense to be settled by supply and demand.

Mr. R. Marshall: The authors place considerable emphasis on the provision of the automatic facilities which electricity offers and feel that the industry has neglected this aspect. I feel bound to say that it has not been neglected by the North Western Electricity Board; articles which have appeared in the leading horticultural journals invariably refer to the automatic methods operated by Lancashire growers.

In Section 4.1.1 two methods of plant irradiation are briefly considered. It is claimed that an advantage of one over the other is that twice as many plants can be treated for the same consumption of electricity. To treat double the number of plants similarly over the same period obviously requires the production of double the amount of light, and I therefore suggest that the consumption is double and not 'approximately the same' as claimed by the authors. Even if the authors' contention is valid, I believe the question of consumption is scarcely worth consideration for this application. For operational reasons and because of the horticultural hazard inherent in the method put forward, I consider it to be quite unworthy as an electrical operation when economically successful alternative methods are available, all of which provide complete automation, at least after working hours.

In Section 3.1.2.1 there is a suggestion that immersion-heater 'conversion sets' may be used for converting existing hot-water systems to electrical operation. We have all been saying for years that electricity is a product known for its flexibility, versatility and rapid conversion to heat when used with conventional apparatus, yet it is suggested in the paper that we should retain a heating method which brings electricity as a medium down to the level of an antiquated heating system, and robs it of the very advantages which we have been claiming for it.

Mr. E. R. Hoare: On any large-scale system of heating, when one makes comparison of costs between electrical systems and other methods, e.g. steam or high-speed hot water, the non-electrical will be preferable, and electrical engineers must understand the advantages of the other systems and not become despondent.

In connection with bench warming, undoubtedly electricity can come into its own. It is not commonly known that the soil when wet will settle at the wet-bulb temperature whereas the air will be nominally at a dry-bulb temperature. The rooting of plants is better if the soil is raised to dry-bulb temperature. This can be done with subsoil heating. It is possible to stop the lowering of soil temperature by putting in electrical misting equipment to stop the evaporation of moisture from the soil and the plants.

The suggestion that existing thermostats are good enough is quite wrong, since most thermostats on the market have neither the differential characteristics nor the thermal inertia characteristics which are required to give the good temperature relationship which low-inertia high-speed hot-water or steam systems make possible. The thermal inertia of these systems is far less than that of the control equipment and it is up to electrical engineers to design suitable equipment.

I disagree with the previous speaker in that very good use can be made of hot-water pipes with electrical heating installed in them. In general it will often work out more economical to install this type of equipment than to use small fans with heaters.

I can appreciate the difficulty in which the authors found themselves over the explanation of plant growth, since they have oversimplified the relationships. Engineers must understand these relationships of plant growth, temperature and light if they are to recommend the proper equipment.

In connection with replacement lighting of tulips, I think it should be made clear that chlorophyll and starch was stored up in the bulb. Mild winter sunshine was equivalent to 28 000 ergs/cm^2, which is nearly 25 watts/ft^2, and even this is not satisfactory for plant growth. It indicates the great difficulty which electrical engineers have to face in searching for suitable replacement lighting.

In connection with sterilization, a figure was given of 3 kWh per hundredweight of soil sterilized. Since this works out at some £600 per acre, which is four times as expensive as steam it is erroneous to think of the electrical method being in wide national commercial usage. For potting soils the small quantity of soil suits the electrical sterilizer.

Whether or not light at Guernsey is better than that at Worthing, it is more important that the degree-day figure is so much better in Guernsey.

The question of automatic ventilation requires close investigation, for in one acre of glasshouses there are 15 tons of air to move for a single change, and to get good climatic conditions and summer sunshine some 60–80 changes an hour are required, i.e. about 1 200 tons of air per hour. That means the use of large-diameter and not small-diameter fans if low running costs are to be achieved.

Mr. A. E. Canham: I feel that further reference to economics would not have been out of place. Electrical methods are essential for efficient horticulture, but their use will only spread rapidly if they are economical. They must have the maximum effect for a minimum expenditure of energy, and that is why the majority of applications mentioned in the paper are either concerned with controlling and regulating or in the provision of an appropriate microclimate for the plant.

I am also disappointed to see how little space has been devoted to light irradiation. The mercury lamp is not an ideal source and every attempt is being made to find a better one. However, its application has been proved to be economical, and I am sure the future will see the technique applied to a wider range of seedlings.

As for maintenance soil-warming, my colleagues and I

set out to discover whether the air temperature in a tomato house could be reduced from 60° to 50° F providing that the soil was maintained at a temperature of 57°–60°, and under our conditions we found that it could not. In fact, maintenance soil-warming had no effect on the yield of tomatoes, even compared with plants also grown at 50° F air temperature but without soil warming. I would not, however, go as far as to say that maintenance soil-warming has no application under any circumstances.

On the subject of mains-voltage cables I should like to make a plea for lower loadings per unit length for cables intended for propagating purposes. A cable rated at 3·75 watts/ft needs to be spaced at 9 in to give a loading of 5 watts/ft^2, and I am sure that this spacing is too great to give uniform heating under the shallow conditions of a propagating bench. A rating of 1½–2 watts/ft would be much more satisfactory.

Mr. F. E. Rowland: Is the statement that there may be damage to tall growing crops from fan unit heaters based on experience, as I have not heard of this happening?

Could information be furnished on the economies which can be effected by double-casing glasshouses with polythene film, and on the possibility of using two layers of polythene in place of glass?

When results of plant irradiation have been unsuccessful, it has generally been due not to a defect in the application but to lack of growing skill.

Plant environment chambers are an important and interesting application of electricity to horticulture. Laboratories, sometimes called 'phytotrons', containing a number of these chambers are widely used, one of the largest and most recent being at Wageningen, Holland. It contains 16 glasshouses and experimental rooms in which the air temperature, humidity and the duration and intensity of light can be controlled. In the five cold rooms artificial illumination up to an intensity of about 30 watts/m^2 is obtainable. The main source of light is high-pressure mercury-vapour lamps, with incandescent lamps to compensate for red deficiency.

Another room at the John Innes Horticultural Institution, Hertfordshire, has a maximum intensity of 1 600 lumens/ft^2, produced by four banks of twenty 6-ft daylight fluorescent tubes suspended from the ceiling.

For sterilizing, capacity of soil should be stated in cubic measurement, because its weight varies considerably with its composition. 3 kWh per hundredweight of soil sterilized is high and 2½ kWh is more realistic.

Electric power for cultivating the land is of high importance from the strategic, utilization, electricity consumption and equipment aspects, and every possibility should be explored. The method most used in practice, and which might well be investigated in this country, employs a power-driven cable reel mounted on the tractor.

Mr. H. R. J. Baigent: Throughout the paper the maximum demands and unit consumptions quoted show load factors of only some 10–15%. If this is so for direct electrical heating, growers must certainly not expect preference over any other industry, Nevertheless, they should not be too hasty in thinking that direct electrical heating is uneconomic. The scarcity of labour, the increasing cost of solid fuel, the vulnerability of oil supplies, and the advent of nuclear energy are all encouraging to the use of electricity. For this reason we should give more attention than we do to the best means of space heating by electricity in glasshouses, and to new ideas and methods.

I believe it might be a most promising proposition to equip a glasshouse with plastic roller blinds to give at will—possibly automatically—either shading or heat insulation, and provide the heating by a combination of intermittently-charged thermal-storage heaters and fan heaters. The thermal-storage heaters would give a measure of heat reserve and might be provided in part in the form of floor heating down the centre path of the house. Airflow heaters for the supplementary heating have merit in providing a ready means of ventilation or air circulation in the summer months and thereby some off-maximum demand units. Such an arrangement combined with those operations for which electricity is an essential might very much improve the load factor.

Mr. Martin M. Harvey: Twelve months ago, in the Midlands Board area, a greenhouse was built 20 ft long × 10 ft wide and equipped with night-storage heating. The metal-sheathed mineral-insulated heating cable was installed in a concrete path 20 ft long × 4 ft wide and 8 in deep which contained 3½ tons of concrete and ran along the middle of the house. The cable was installed 2 in below the surface with a loading of 30 watts/ft^2. At the same time the cavity walls of the house were insulated with glass fibre and approximately 2·5 kW of the same type of cable was installed in the cavity. Thus, approximately half of the total load of 5 kW was in the floors and half in the walls, and this was sufficient for normal frost protection (with an inside air temperature of 45° F). Much of the heat in the walls was lost to the outside air, but the half-load in the floor could maintain a 20° F rise when heat was injected into it for 12 hours at night.

Having now increased the loading of the path to two-thirds of the total of 5 kW a 25° rise is obtained. Thermographs have been installed and we have discovered that the plants getting irradiation from the floor are not adversely affected. The heat in the house is near the floor, as in normal night-storage heating of offices and schools. With any other form of heating system it is possible to obtain a calculated definite degree rise irrespective of the inside temperature of the house. This is not so with a hot-path system, since the path will give a maximum heat output only when the outside temperature is low, and when the inside air temperature of the house is equal to that of the path no heat will flow. If the sun increases the temperature of the air above that of the path heat will flow from the air of the glasshouse into the path, and the path will not be switched on for so many hours the next night. It is, therefore, self-regulating in a crude way.

We have several installations, both inside and outside houses, of night-storage propagating frames and benches with loadings of 10–12 watts/ft^2: these are used for lettuces and chrysanthemums. With outside frames the temperature in the frames is remarkably steady over a wide fluctuation of outside air temperatures.

We consider that for the amateur requiring frost protection in glasshouses or for propagation work night-storage systems can be a satisfactory solution.

Mr. E. C. Claydon: Apparently the reason for lack of interest in the authors' plant-irradiation proposals is related to the choice of the variety of tomato in which the grower is interested. Would the authors tell us whether it is a fact that different varieties of tomatoes respond in different ways to the irradiation?

I notice that there appears to be a conflict of opinion between the authors and others on the single- and double-batch methods of lighting. It seems that there may well be a case for both methods. One speaker mentions 70 kW installations, and I can imagine that moving lamps in an installation of that kind would be a trial to the grower. Perhaps that is a case for automatic control, but for smaller installations no doubt the method advocated by the authors is the better.

With regard to ventilation, I would say that there is at least one installation operating where 5 ft diameter fans are employed for recirculation. I do not think that the installation attracted a great deal of attention in the electricity industry, but the grower

seems satisfied with the results, and I should like to know whether the authors feel that the system has some promise.

On the question of the use of electricity in space heating, I think there is a big market for the suppliers of electrical heating equipment in the case of hand-fired solid-fuel installations. We have heard a great deal about wonderful automatic heating installations of great magnitude, but we must remember that there are hundreds of little nurseries with hand-fired boilers, and I think that others will confirm that the ordinary hand-fired boiler has a habit of fading out at about 4 a.m. Electricity Boards are interested in a heat load at 4 a.m., and the authors might confirm that there is some use here for electrical heating as a standby for hand-fired solid-fuel installations.

There is one application which seems to have been neglected, namely the use of electrical heating for the curing of corms and sets. Have the authors anything to say on this subject? We have one or two small installations which have had good results reported and it seems that here is a modest but interesting application.

[The authors' reply to the above discussion will be found on the next page.]

NORTH-WESTERN UTILIZATION GROUP, AT MANCHESTER, 12TH FEBRUARY, 1957

Dr. A. J. King: A thin sheet of plastic material fastened to the wood framing on the inside of a greenhouse might be effective in reducing the heat dissipation, since the layer of air between the glass and plastic film should have considerable thermal resistance.

Mr. R. Marshall: The authors draw attention to the low thermal capacity of commercial glasshouses, yet suggest the connection of electrical equipment to existing hot-water heating installations of high thermal capacity. This method, with its sluggish response, obviously robs electricity, as a heating medium, of most of its advantages.

In Section 4.1.1 the authors claim substantial electro-economic advantages of one method of irradiating tomato seedlings over another. The cost of irradiating sufficient tomato seedlings to plant out an acre of glass has been found to be £100 or perhaps a little more. The revenue to the grower from an acre of irradiated plants should be at least £8 000. The substantial economic advantage claimed could be little more than £25 or £30 against a revenue of £8 000 and this is only theoretical. The authors have failed to state in the paper that it is necessary for the nurseryman to move his irradiators from one batch of plants to another and to erect light-proof screens not earlier than 11 p.m. each and every night, which can be a very trying operation.

Dr. A. H. Parkinson (*communicated*): Important additions to the examples of direct electrical heating given in Section 3.1.2 are:

(*a*) Where electrical heating is supplementary to an already existing system which is normally sufficient to maintain adequate temperatures but which may in severe weather prove inadequate.

(*b*) Where electrical heating is used for short periods to maintain relatively low temperatures. It is sometimes possible to produce chrysanthemums in cold houses until November, but one frost in late September or October can ruin the crop. Hot-water systems must be kept in operation continuously in case of a sudden frost. Electrical fan heaters would ensure that the crop was carried through until completion or until it was uneconomical to use heat any longer. Running expenses are limited to those few nights when the temperature falls to a low level.

I do not agree with the broad statement given under (*c*) of Section 4.1. Admittedly the duration of light has a great influence on the development of many plants towards flower production, but it does not control this development. With chrysanthemums, day length and temperature determine the time of flower production. With tomatoes, temperature has a great influence on the time of flower production and on the number of flower buds, but a tomato plant will produce flowers in any day length in which it can live.

In Section 4.1.2 information is given regarding the delaying of the flowering period of chrysanthemums by increasing the day length at the time of bud formation. Exactly the same effect can be produced by giving a short light period in the middle of the dark period. The cost of this method is much less than that quoted in the paper.

Incidentally, the extra light must be started before bud initiation has started, not 'at the time of bud formation', if satisfactory blooms are to be produced.

[The authors' reply to the above discussion will be found on the next page.]

SOUTH-WEST SCOTLAND SUB-CENTRE, AT GLASGOW, 27TH FEBRUARY, 1957

Mr. J. W. Moule: In the south of Scotland electrical off-peak space-heating is making considerable inroads into fields which hitherto have been almost exclusively the preserve of solid fuel and oil. It is therefore disappointing to hear the authors' view that, as regards space heating of glasshouses, electricity's only part will be the supply of auxiliary power to coal- or oil-fired boilers. In Section 3.1 they admit that electricity at 1d. per kWh would be competitive with solid fuel or oil. Electricity is available at this price under off-peak tariffs, but no doubt from experience in the south the authors discount the possibility of off-peak electricity being suitable for glasshouse space-heating.

I would draw the authors' attention to the particularly favourable off-peak tariffs available in the south of Scotland. Under our No. 2 off-peak tariff a supply is interrupted only between 8 a.m. and 10 a.m. and between 3 p.m. and 5 p.m., the inclusive charge at present being 0·86d. per kWh. Do the authors feel that a short interruption in supply of only two hours would have harmful effects even in very cold weather? Even if it did, it would be possible to supply some thermal storage in the way of electrical floor-warming or by using block storage heaters in the glasshouse. Another possibility would be the replacement of the ordinary solid-fuel or oil-fired boiler by an electrical water heater with adequate hot-water storage. There seems, therefore, no reason why off-peak electricity should not be used for glasshouse space heating and, at 0·86d. per kWh, on the authors' admission it should compete favourably with other fuels.

I would like to comment on the authors' recommendation that a minimum outside temperature of 20° F should be assumed when designing glasshouse space-heating installations. I feel it is dangerous to generalize on this matter in view of the considerable variations experienced from place to place in a hilly district such as the south of Scotland. Reference to H.M.S.O. publication 'Averages of Temperature for Great Britain and Northern Ireland 1921–50' will illustrate the wide variations possible from place to place. As an example of this I would refer to a large well-insulated building at Innerleithen where extremely cold conditions are experienced. In designing the

space-heating installation it was necessary to assume a minimum outside temperature of 20° F (as compared with an average figure of 28° F). Surely any glasshouse heating installations in the same neighbourhood should be designed for a much lower minimum temperature than 20° F.

I found in the paper no guidance as to the amount of ventilation required in glasshouses, the only reference being at the end of Section 7, where a fan was said to be capable of 33 air changes per hour. Surely an air change of this order would produce conditions approaching those in a wind tunnel? Perhaps the authors could give some idea of the number of air changes needed for successful cultivation. If the air within a glasshouse required to be changed at a high rate, this factor would have an important effect on space heating, as the heat loss due to air change would necessitate a substantial increase in the output of the heating plant. It is a pity that the authors do not bring out this point in Section 3.1.2.2, in which they deal with the design of the space-heating installation.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. C. A. Cameron Brown and A. W. Gray (*in reply*): We are very grateful to Mr. Graham Sparkes for putting the grower's case so clearly. It is obvious that Mr. Sparkes, one of our very up-to-date growers, not only realizes the benefits which electrical development so far can give to the grower, and is taking advantage of them, but is looking forward to the further development and uses of electricity in horticulture. The close collaboration between the grower and the electrical engineer for which he pleads is, of course, essential to any real progress.

Mr. Marshall deprecates the use of electrical conversion units for existing hot-water systems. While we realize that response from such an installation is not as precise as for the other types of equipment suggested in the paper, we still feel that in view of the large number of low-pressure hot-water installations in the smaller and amateur greenhouses the conversion unit provides an economical way of changing from solid-fuel to electrical space heating, and while not ideal, is certainly preferable to the uncertainty of the small solid-fuel boiler. The second point he raises is on the question of the single- or double-batch system of irradiating tomato seedlings. The essence of the difference between the two methods is that with the single-batch method each lamp irradiates 160 plants per run, whereas with the double batch system, each lamp irradiates 320 plants per run. Consequently, as the propagating season for early tomatoes is very limited, the alternative where the single-batch method is used is to install double the number of lamps. This would not only increase the capital cost to the grower, but in areas where a maximum-demand charge is in force, would double this charge, thus further penalizing the grower. The suggestion that the necessity to move the lamps from batch to batch and to erect screens between the two batches constitutes a 'horticultural hazard' is not sustained in practice.

Three speakers, including Dr. Parkinson, have taken us to task for our over-simplification of horticultural terms. This is no doubt a deserved rebuke, but space forbade giving the full explanations which would be required by the plant physiologist.

Mr. Hoare emphasizes the interesting fact of the difference of temperature at bench level and in the air. The difference in such temperatures measured on a number of installations has been as much as 6° F lower immediately over the bed, and as this is in most cases detrimental to the plant, it constitutes a very valid case for the use of electrical soil warming on most propagating benches. Mr. Hoare is in error in concluding that we have recommended *in-situ* sterilizing of the glasshouse growing area, since, in fact, our only reference was to batch sterilizers of such capacity as obviously to be intended for sterilizing soil for potting compost.

Mr. Canham expresses disappointment that little space has been devoted to light irradiation. This application of electricity is, of course, of tremendous importance and only now beginning to be developed. It is, however, such an important and involved subject that it might very well form the subject of a paper on its own.

Several speakers raised the question of thermal-storage heating for glasshouse space heating, and the report on the trials being carried out in the Midland Board area as described by Mr. Martin Harvey is of particular interest. From the results obtained so far it would seem that this is an investigation well worth continuing, but it must be borne in mind that the changes in temperature in a glasshouse are quite wide and occur rapidly, and if this method of heating allowed wide temperature swings the plants would suffer correspondingly. The alternative suggestion by Mr. Moule of using more orthodox forms of electrical space heating for the greater part of the day and tiding over restricted periods with storage heaters is, of course, dependent on a favourable off-peak tariff such as is available in South Scotland. Mr. Moule also suggests the alternative use of electrical water heaters with adequate hot-water storage, but for large areas of glass the storage required would be enormous and even at one penny per unit not competitive with up-to-date solid-fuel and oil-heating installations.

Dr. Parkinson suggests using electric heating in glasshouses where frost protection only is required, and this is, of course, practised in areas where a sufficiently favourable tariff is available. Several speakers have raised the question of automatic ventilation. Figures quoted by Mr. Hoare will give some idea of the magnitude of the task involved in ventilating large blocks of growing-houses; work so far done has shown that the weight of air is not the only problem, but for a smaller house of the propagating type the difficulty is not so great. Mr. Hoare's reference to air changes of up to 60 or 80 per hour will answer Mr. Moule's query on the amount of ventilation likely to be involved. This high rate of air change will, however, only be required during the summer months and so will not affect the heating cost. During the period when heating is required automatic ventilation should only be operated at a temperature above that at which the thermostat controlling the heating installation is set.

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SOME ASPECTS OF HEAT PUMP OPERATION IN GREAT BRITAIN

With particular reference to the Shinfield Installation

By MIRIAM V. GRIFFITH, B.Sc., F.Inst.P.

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SUMMARY

Heat-pump operation in Great Britain is reviewed from the point of view of the electricity supply industry. The factors which have to be taken into consideration for possible applications are discussed, e.g. sources of low-grade heat, capacity required and special methods of utilization.

British experience, including the results of laboratory investigations on heat transfer from the soil and other aspects, is described. Details of construction and operation of a practical 10 h.p. heat pump, installed to warm a laboratory building, and using the earth as its source of low-grade heat, are given. Observations of performance include load factor and maintenance and attendance.

The economic aspect is dependent on the present state of development, but future improvements together with comparisons with other methods of performing the same duties are considered. The paper concludes with a discussion of the value of the heat pump as an electrical load.

(1) INTRODUCTION

In December, 1852, William Thomson, later Lord Kelvin, published an article entitled 'On the Economy of the Heating or Cooling of Buildings by means of Currents of Air' in the *Proceedings of the Glasgow Philosophical Society*. It was accompanied by a mathematical investigation of the operation of the machine now known as a heat pump. In June, 1881, a further article appeared stating that the principle had been successfully applied for cooling. It ended rather wistfully,

> The method of heating air described in the article remains unrealized to this day. When Niagara is set to work for the benefit of North America through electric conductors, it will no doubt be largely employed for the warming of houses over a considerable part of Canada and the United States. But it is probable that it will also have applications, though less large, in other cold countries, to multiply the heat of coal and other fuel and to utilize wind and water power (with aid of electric accumulators) for warming houses.

In the event, it was not until another fifty years had passed that any real effort was made to use the principle for such purposes.

(1.1) Basic Thermodynamic Principles of the Heat Pump

The efficiency of an ideal heat engine is given by the expression $W/Q = (T_1 - T_2)/T_1$, where W is the work obtained, Q is the heat supplied, T_1 is the temperature at which the heat is available and T_2 is the temperature to which the heat is reduced in doing the work W. Both T_1 and T_2 are measured in degrees Kelvin. Since this ideal cycle can be shown to be reversible, a quantity of power can therefore be used to transfer heat from a low level of temperature to a higher useful one; the ratio of Q, the heat output, to W, the work done by the source of power, being given by the reciprocal of the heat-engine expression, i.e. $Q/W = T_1/(T_1 - T_2)$. The practical process entails a supply of heat at temperature T_2 so low that the heat is not useful, a local use for heat at a rather higher temperature T_1, two heat exchangers, a working medium and a heat engine driven by an external source of power such as electricity or oil. The heat from the low-temperature source is transferred to the working medium in the first heat exchanger, mechanical work is performed on the medium in the heat engine and heat is rejected in the second heat exchanger from the working medium to a process in which it can be used at the temperature T_1.

However, since a theoretically perfect engine cannot be achieved, the energy ratio given by the above formula cannot be attained and the practical performance of a heat pump is best described by the *performance energy ratio* (p.e.r.), which is the ratio of the heat output at T_1 to the input to the heat-engine system and which takes account of all the local inefficiencies. The best values of p.e.r. so far obtained are about 50% of the ideal ratio given by $T_1/(T_1 - T_2)$, but the advantage of the system for fuel-saving is considerable even so, p.e.r. values of three and upwards being readily obtainable, while values of up to 20 have been found in special circumstances.

(1.2) The Fuel-Saving Aspect

At present the use of the heat pump involves a higher capital cost than other devices for the production of heat. Since in most cases it comprises moving machinery, maintenance may be greater than for alternative simpler systems of greater running cost. However, in any process where a high-grade fuel such as electricity must be used, the heat pump shows up favourably. The effect of the high capital cost is also ameliorated in applications characterized by high load factors.

The extent to which the electricity supply industry should foster the development of the heat pump is at first sight limited to those applications for which electricity is the best or only motive power. For certain purposes the direct use of steam in absorption heat-pump systems, as opposed to the mechanical systems implicit in the above discussion, may offer economy to the industry for its own internal heating purposes, especially when the heat at the lower temperature T_2 is available as waste heat in turbine-condenser cooling water.

Alliance with thermal storage will, however, be favourable, since the size of the high-capital-cost plant may thus be reduced. Since the heat-pump process necessarily involves the cooling of a medium, the capital cost of the heating effect can be substantially decreased if this heating can be combined with necessary refrigeration.

(2) AVAILABILITY OF LOW-GRADE HEAT SOURCES FOR USE WITH THE HEAT PUMP

(2.1) Natural Sources

Natural sources are all likely to be at temperatures below 50° F. In Great Britain, river and lake water is available for most of the heating season at 40° F or above, and even in very wintry conditions the temperature should not drop below 38° F if supplies are drawn from a sufficient depth. Where a river or lake con-

This is an 'integrating' paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

Miss Griffith is with the British Electrical and Allied Industries Research Association.

tinuously receives waste-process heat, somewhat higher water temperatures are available.

Air temperatures may drop well below freezing point for several weeks in the year, but the average winter temperature in Great Britain is 40–45° F. The use of external air as a source for a heat pump is complicated in this country by the prevalence of high humidities, since large deposits of frost on evaporator surfaces are to be expected.

Heat from the soil, of course, is abstracted when ground water or wells are used as heat sources. The practicability of direct heat transfer from all soils to buried chilled pipes has not yet been completely established, but research is being carried out.

(2.2) Higher-Temperature Heat Sources, e.g. Industrial Waste Heat

Waste heat exists at temperatures of 70°–120° F in water used for cooling purposes for mechanical and electrical processes in general, and in hot water contaminated in use and then sent to waste (e.g. by restaurants, hotels, hospitals and houses).

In urban areas, many underground substations need expensive ventilation because of the heat from distribution transformers, and there are generally commercial premises at hand which require heating. In both deep mines and underground railways expensive cooling arrangements must be provided irrespective of any heating needs. Hot water can be provided by the use of the heat pump, and, at the mines, it can be conveniently used in pithead baths.

In some cases, waste heat at temperatures above 120° F exists in media that cannot be used directly (e.g. from radioactive sources). This heat must then be salvaged by the use of heat exchangers, with a consequent fall in temperature, and a heat pump becomes necessary for its utilization. No new heat-transfer problems are involved, provided that corrosion is unlikely.

(3) UTILIZATION OF HEAT-PUMP OUTPUT

Since an attractive p.e.r. can only be obtained when the temperature lift is small, and since commonly available refrigerants are efficient only over certain temperature ranges, the output of heat pumps using natural sources is limited at present to about 120°–160° F. Table 1 illustrates the most probable conditions of heat-pump application. The values of p.e.r. given in col. 6 take into account the probable efficiencies of the plant. The figures quoted for natural sources represent the temperatures to be expected under the most unfavourable conditions. In the case of air, the size of plant is determined by the lowest source temperature, although this is only likely to exist for a very small fraction of the heating season. The values in col. 7 represent published achievements to date for the appropriate conditions. Comparison with col. 6 indicates the scope for improvement in practical application.

(4) INFLUENCE OF DIFFERENT DRIVES ON PERFORMANCE

When flexibility and amenity are unimportant, heat pumps may be driven by internal-combustion or gas engines. Higher output temperatures for the same p.e.r. are possible with these drives if the waste heat from the engines is fed into the system. Broadly speaking, the effective p.e.r. of an electrically-driven heat pump can be doubled by replacing the electric motor by a Diesel engine fitted with a waste-heat boiler, at an added cost for the heat pump as a whole of 10%. For a specific application this means that the capital cost of a Diesel-driven installation may be only about 55% of one having an electric drive. The probable running costs and the overall fuel-utilization efficiency are equally favourable. A gas engine shows up less favourably from the point of view of fuel-utilization efficiency, since the production efficiency of gas must be taken into account.

Table 1

MOST PROBABLE CONDITIONS OF HEAT PUMP APPLICATION

Use for heat	Heat distribution medium	T_1	Source of low-grade heat	T_2	Values of p.e.r. possible	Values of p.e.r. achieved
		deg F		deg F		
Space heating	Air	90–100	Air	25	5·9	4·0
			Exposed water	38	6·9	5·2
			Ground water	50	8·2	5·5
			Soil	32	6·5	5·0
			Waste heat	70	11·5	6·0
			Waste heat	80	14·1	6·0
Space heating	Water	120	Air	25	5·1	3·2
			Exposed water	38	5·7	4·3
			Ground water	50	6·5	5·0
			Soil	32	5·4	4·0
			Waste heat	70	8·5	6·0
			Waste heat	80	9·7	6·0
Hot water storage* and utilization	Water	140	Air	25	4·4	3·0
			Exposed water	38	4·9	3·7
			Ground water	50	5·5	4·0
			Soil	32	4·7	3·5
			Waste heat	70	6·7	5·0
			Waste heat	80	7·3	5·5

* The possible use of hot water for soil heating and other horticultural work may be included.

(5) POSSIBILITY OF THE EXTENSION OF USE OF THE ELECTRICALLY-DRIVEN HEAT PUMP

The heat pump is at an earlier stage of development than any competing method, and it is reasonable to expect that, with experience, its cost will be reduced and its efficiency increased proportionately more than those of its competitors in a given time, so that its field of utility should be widened. In examining how this may take place, using broadly the present techniques, it is convenient to consider three separate classes, namely large installations (above 150 kW heat output), medium-size installations (10–150 kW heat output) and small installations (below 10 kW output and including fractional-horse-power units).

(5.1) Large Installations

When a demand for a large quantity of heat exists, the cost of fairly detailed investigation of possible alternatives is justifiable. In the case of the heat pump, sufficient successful examples already exist for reliance to be placed on the achievement of designed performance, particularly when water sources are used. The most important immediate target is the production of cheaper components. The reduction or recuperation of electric-motor losses in this range will not materially affect the economics. However, it is only from experience gained in this more favourable field that the use of smaller heat pumps is likely to increase, and thus expenditure on pilot schemes in excess of that economically justifiable is of great value.

(5.2) Medium-Size Installations

In medium-size installations detailed investigation of the cost of individual schemes is unlikely to be possible and the heat pump will be adopted only when the financial advantage is clear. Improved compressor efficiency is important, and the recuperation of electric-motor losses is desirable.

It is in this range that the non-industrial sources of waste heat are likely to be found (hotels, restaurants, etc.). In rural areas, where the heat pump is especially attractive if account is taken of the transport costs of alternative fuels, the use of septic tanks or cess pits as heat sources might be considered.

(5.3) Small Installations

The greatest potential market exists where domestic application is possible.

In this range, electric-motor losses become of importance, and their incorporation in the heat cycle should be considered. The development of higher-efficiency compressors and larger hermetic units would be of value.

The load factor of space heating can be very poor; that of water heating is somewhat better. Given the possibility of satisfactory sources, however, there are attractive possibilities in the provision of heat pumps for water heating and seasonal base-load space-heating equipment. Alliance with thermal storage would improve the load factor.

For domestic use there is also the possibility of development of dual-purpose units, i.e. where the cooling as well as the heating properties of the heat pump can be utilized, either concurrently or alternatively.

(6) BRITISH EXPERIENCE WITH HEAT PUMPS

The electricity supply industry has already played some part in practical investigations on the possibilities of the heat pump, since three units have been in operation for several years at two Midland generating stations. In 1947, the Electrical Research Association was asked to carry out laboratory tests to establish the performance of small units (5 h.p.) under various conditions of use. The heat transfer from low-grade heat sources of various types was also studied.

(6.1) Heat Transfer from the Soil to Buried Chilled Pipes

In the case of flowing water and moving air a considerable body of information on heat transfer already exists. The soil, however, possesses two of the desiderata of useful sources: it is abundant in quantity, and contains stored heat it has absorbed from direct solar radiation. The rate of flow of this absorbed heat through the soil depends on several factors, however, and it is not enough to measure the local heat transfer for short periods, say to buried horizontal chilled pipes, but tests must be continued for a time sufficiently long to establish the rate at which heat flows in from surrounding regions to replace the heat abstracted locally.

Tests on the heat transfer to chilled pipes in a clay soil at the laboratory, which were carried on for sixteen months, established the following:

(*a*) For copper pipes laid in horizontal grid formation in clay soil in the London area, at depths down to 6 ft from the surface and at least 1 ft apart, the steady rate of heat absorption is as much as 30–60 B.Th.U./h per lineal foot of $\frac{1}{2}$–1 in-diameter pipe, the optimum diameter being $\frac{3}{4}$ in.

(*b*) The absorption rate does not vary appreciably with depth of burying between 3 ft and 6 ft from the ground surface.

(*c*) The temperature difference between the cooling medium in the buried pipes and the undisturbed soil must be kept to about 20° F, i.e. the optimum temperature of the cooling medium is between 22 and 25° F. When the cooling medium is calcium-chloride brine, the rate of flow should be between 30 and 35 lb/min.

Subsequently other test sites were set up to study different soils, and the research is still continuing.

(6.2) Evidence of Satisfactory Performance of Heat Pumps

The study of the 5 h.p. heat pump unit referred to previously showed that:

(*a*) Water at a temperature suitable for panel radiators (130° F) can be obtained with a heat pump operating at a p.e.r. of 3·0, if the source of low-grade heat is between 40 and 50° F.

(*b*) Avoidable sources of inefficiency are pressure drops in connecting pipework and loss of heat from the condensing heat exchanger and connecting pipework surfaces.

(*c*) Some advantage in performance may be obtained by the use of a suction-line heat exchanger, in addition to the main heat exchangers referred to earlier.

(*d*) The cheapest and most effective method of control of output for plants of medium size is to switch the motor on and off by means of a thermostat.

In order to gain practical experience, a heat pump was installed in 1951 to heat a laboratory building at the E.R.A. agricultural establishment at Shinfield, near Reading. Some attempt was made to justify the installation on an economic basis, and this was fairly successful in the particular circumstances. Provision of access for fuel lorries, storage of fuel and the cost of boiler attendance would have cancelled to a large extent the extra capital cost of the heat pump.

Fuel transport and attendance would not have been necessary with gas, but the running cost would have been high. The use of oil was considered, but at the time there was some lack of confidence in the certainty of future supplies.

(6.3) Design of the Shinfield Heat Pump (Preliminary Considerations)

The only source of low-grade heat, except for air, available in any quantity at Shinfield is the soil, which is mainly clay. Although calculation of the heat load showed that a heat pump driven by a 10 h.p. motor would be needed, and that the necessary rate of heat abstraction from the ground would be of the order of 16–20 kW, the results of laboratory investigations on such sources were thought to give sufficient evidence to justify the installation, although its capacity would be greater than any other existing plant operating on this source.

The heat distribution in the laboratory is by means of panel radiators of pressed steel, the total area being sufficient to provide the maximum heat load with a water temperature of 120° F.

(6.4) Details of the Shinfield Installations

The heat pump was constructed by the staff of the Association from components purchased from several manufacturers. The installation, a schematic of which is shown in Fig. 1, consists of the following:

(*a*) A 10 h.p. H-type reciprocating compressor with belt drive. The electric motor is of the slip-ring type and is provided with automatic and manual starting arrangements.

(*b*) A heavily-insulated shell-and-tube double-pass condenser rated at 100 000 B.Th.U/h for Freon 12 at 130° F. The maximum design working pressure is 200 lb/in^2.

(*c*) An evaporator of the spiral Rosenblad type rated at 80 000 B.Th.U./h. The plant was not designed to be reversible, so that the maximum working pressure for this is 50 lb/in^2.

(*d*) A thermostatic expansion valve capable of handling the design load and to provide a pressure drop of 170 to 20 lb/in^2.

(*e*) An oil separator, the function of which is to collect oil escaping from the compressor in the heated vapour and to return it to the crankcase.

(*f*) A liquid receiver large enough to hold all the refrigerant charge required for the installation in case of emergency. Since the contents of this vessel will be warm during operation and it is desirable to cool the refrigerant liquid at this stage, a jacket was provided covering most of the outer surface, i.e. the arrangement became a combined liquid receiver and suction-line heat exchanger.

Together with the connecting copper pipework, these six components form the heat pump proper. To collect and distribute the heat, to control the operation to provide the desired conditions, and to prevent damage due to external conditions outside the design range, the following auxiliary items are included:

(6.4.1) Low-Grade Heat-Collection System (Final Arrangement).

Since sufficient ground area was not available to install the 2 000 ft of $\frac{3}{4}$ in-diameter pipe required to collect heat from the

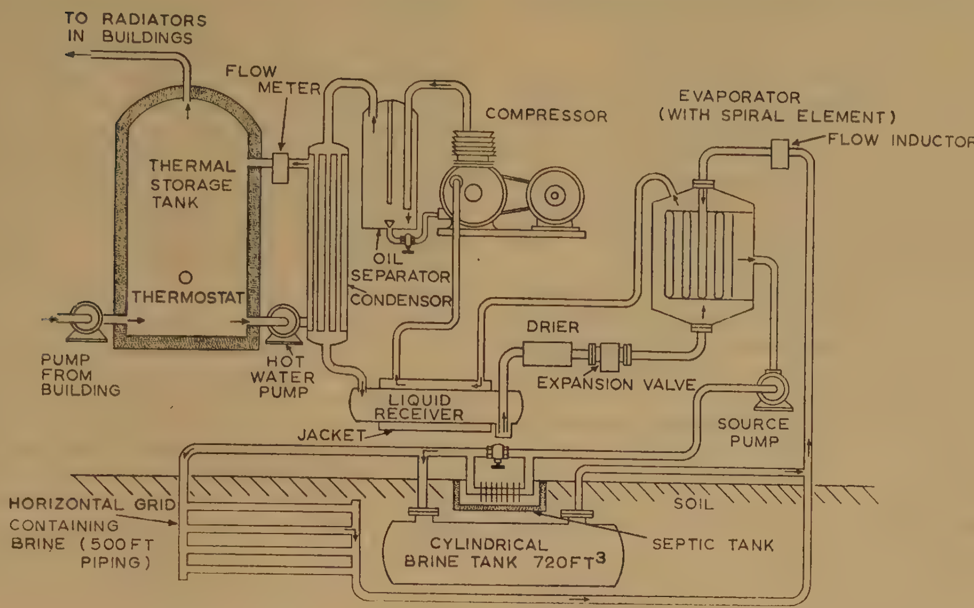

Fig. 1.—Schematic of heat pump at Shinfield.

ground at the rate of 20 kW (68 200 B.Th.U./h), the main source of low-grade heat is a cylindrical tank having a volume of 720 ft^3. The tank, 5 ft 6 in in diameter and 30 ft long, was originally the shell of a Lancashire boiler. In addition, 500 ft of pipe are buried horizontally at a depth of 3 ft beneath a lawn separating two laboratory buildings, the pipes being spaced 1 ft apart. This grid is in parallel with the main flow through the buried tank.

A certain proportion of the main flow of heat-collecting medium from the large buried tank passes through a small coil immersed in a septic tank.

The heat-collecting medium is circulated continuously through the tank, grid and coil evaporator by a 0·75 h.p. circulating pump.

The hot water from the heat-pump condenser is circulated to and from a small thermal-storage vessel by a pump. From this it passes when required to the radiators in the laboratory, the action of the pump providing this secondary circulation being controlled by a time switch. The on-off operation of the heat-pump compressor is controlled by a thermostat situated near the base of the storage vessel. A certain amount of thermostatic control is also provided in the laboratory.

(6.4.2) **Safety Devices.**

There is little potential danger to personnel from the heat pump, but high-pressure cut-out switches are installed to stop the compressor should the pressure rise above a certain limit; with Freon 12 in the Shinfield system this is 200 lb/in^2. Since an abnormally low suction pressure is usually a sign of a blockage in the system or of insufficient refrigerant charge, a low-pressure cut-out switch is provided to give warning of this.

Since the refrigerant in a heat-pump system working with a low-grade heat source of about 40° F is probably below freezing point when the compressor is working, it is essential that the heat-collecting medium be kept circulating, since expansion due to freezing may burst the evaporator tubes. A flow-sensitive relay is therefore incorporated in the evaporator pipework carrying the heat-collecting medium. This relay, which is of the type which fails to safety should its operation become faulty, operates to stop the compressor motor should the flow drop below a safe level.

(6.4.3) **Direct Comparison with a Conventional Heating System.**

An adjacent laboratory of similar size and shape also required heating at the period when the heat pump was being considered. A gas boiler feeding hot-water radiators of the conventional 'convective' type was installed, the boiler itself and a great part of the flue being inside the building. The rating of the boiler was 100 000 B.Th.U./h, i.e. slightly higher than the heat output expected from the heat pump, but the next standard size had too low an output. Forced circulation was used for the hot water, which was kept at a temperature of 180° F by a room thermostat. This installation was set up entirely by a commercial firm and was inspected by officials of the local Gas Board before use.

(6.5) Study of the Operation of the Heat Pump

The overall p.e.r. of the system is given by the heat supplied to the actual building requiring to be warmed divided by the total electrical input to the compressor motor and the auxiliary pumps. The p.e.r. of the heat-pump installation is given by the heat output of the condenser divided by the same electrical input. The p.e.r. of the compressor alone is given by the heat output of the condenser divided by the electrical input to the compressor.

To study the performance it is necessary to record the rate of use of electrical energy of the auxiliary items and the compressor motor separately. The heat output of the condenser is given by the temperature rise of the water passing through it, multiplied by the rate of flow of this water. The heat absorbed by the laboratory building is given by the temperature difference between the flow and return pipes entering the building, multiplied by the rate of flow of the water circulating through the radiators.

The heat output of the condenser should be balanced against the sum of the heat abstracted from the heat source, in this case the soil, and the heat equivalent of the work of compression. Stray heat may be absorbed from the heat-pump chamber air on the low-temperature side of the system, and rejected to the air through the insulation on the high-temperature side. The efficiencies of the evaporating and condensing heat exchangers are therefore affected by the conditions *in situ*. The efficiency of the compressor is given by the work of compression done on

the refrigerant passing through it divided by the energy absorbed in doing this work.

(6.5.1) **Factors Affecting the Component Efficiencies.**

Adequate lubrication of the compressor is essential for minimum maintenance. The oil separator is not perfectly efficient and some oil may be deposited on the heat-exchanger surfaces. However, the rest should be returned with the suction vapour from the evaporator to the compressor crankcase, although, to ensure this, the vapour velocity in the low-temperature suction lines must not fall below 2000 ft/s for Freon 12.

The deposition of oil on the heat-exchanger surfaces, together with fouling by scale, dirt and rust of the water-side surfaces, will add gradually increasing surface resistances to the heat transfer across the walls of those heat exchangers. To maintain efficiency it is necessary to clean these components about once every two years. The deposition of dirt may be largely prevented on the evaporator side by the provision of a filter.

The presence of air causes higher head pressures for the same output temperature, increases the necessary brake horse-power of the compressor and promotes oxidation of the lubricating oil.

Heat-pump systems must be completely free from leaks, and it is desirable that regular testing be carried out. Shortage of refrigerants leads to low suction pressures and reduction both of p.e.r. and system heating capacity.

Although in theory the efficiency of compression is greater for a 'wet' high-pressure vapour than for a superheated vapour, practical conditions combine to demand a certain degree of superheat. In addition, sub-cooling of the liquid refrigerant after condensation is desirable. The sizes and arrangement of components of the heat pump should be designed to provide this superheating and sub-cooling.

(6.5.2) **The Heat Load and the Heat Source.**

If the rate of heat loss from the building to be heated is less than the maximum rate of heat output of the heat pump at the design condensing temperature and the available source temperature, the system will provide hot water at the desired temperature, and control of operation will be a simple on-off cycle. However, if the heat load is greater than the maximum heat output the condensing pressure and temperature will fall. However, the heat pump has an advantage over direct heating systems similarly undersized for emergency heat loads, because its p.e.r. rises as the condensing temperature falls for a constant source temperature. Some 'cold comfort' may therefore be derived from the thought that the load on the electricity supply per kilowatt-hour of heat output has actually decreased at a time of increased demand, although the deficit in the heat supplied by the heat pump is no greater than that of an electrical or other appliance of constant loading.

The maximum heat load for the Shinfield heat pump was calculated from the accepted thermal constants of the laboratory building structure for an air temperature of 65° F maintained inside the building against an external ambient temperature of 30° F. The same calculation was made for the adjacent laboratory to be heated by a gas boiler. Both laboratories were insulated to the standards recommended by the Egerton Committee, namely the transmittance U of the walls was slightly less than 0·2 B.Th.U./ft^2 per hour per deg F difference between the inside and outside air temperatures. In both cases a calibration was carried out.

For four consecutive heating seasons, the daily gas consumption in one laboratory, the electricity consumption for the heat pump and the daily indoor and outdoor temperatures have been recorded. The rate of heat loss of the building could be expected to vary with wind and rain and drying out owing to solar radiation, but the variation in daily consumption per degree Fahrenheit difference between the inside and outside air temperatures was much greater than would be accounted for by these agencies. It was concluded that conditions of building use, i.e. the opening of doors and windows on warm days, the use of experimental ovens and the presence of varying numbers of investigators was also effective. The same conditions would, of course, apply to the laboratory heated by the heat pump, although in this case the electricity consumption would also vary with the temperature of the heat source.

The behaviour of the soil heat source has been reasonably satisfactory. At the beginning of the first year the 720 ft^3 buried tank and its connecting pipes provided the whole of the low-grade heat when filled with water. After two months (October and November) the temperature of the water entering the evaporator was 36° F and freezing was occurring at the exit. After an interim period during which a small proportion of mains water was added to the water circulating through the buried tank, the freezing point of the latter was reduced by degrees to 20° F by the addition of calcium chloride. The resulting solution was made slightly alkaline to inhibit corrosion of the buried pipes. Calcium chloride was chosen because the large volumes concerned made pleasanter alternatives too costly in this case, and, in all, some four tons were added. With the buried tank used alone, even the brine froze at the exit of the evaporator at the end of February in the first year of operation. The horizontal grid referred to in Section 6.4.1 was therefore added to the system, together with the small coil immersed in the septic tank. At the end of the winter of 1954, more calcium chloride was added, bringing the freezing point down to 16° F. In the winter of 1955–56 continuous operation without freezing was achieved.

Although several loads of sand were used to line the excavated pit in the clay in which the 720 ft^3 tank was buried, with the object of improving the local heat transfer, the ground has fallen in temperature more rapidly each year. In early 1952, the brine temperature entering the evaporator stabilized at 26° F. In early 1955 it stabilized at 21° F. It is possible that this decrease is due to deterioration of the thermal contact between the soil and the surface of the tank. The flow of heat towards the buried chilled body involves the movement of soil moisture also towards that body and consequent local freezing of a high-moisture-content soil. On thawing, the density of particles of soil per unit volume close to the tank is small and falling away may occur. This action has been observed on a test site with buried chilled pipes but has not been established definitely for the tank.

Fig. 2 shows the temperature of the undisturbed ground at the heat-pump site and also that of the brine leaving the evaporator, as functions of time, the date of the period of observation for the soil being 1st December, 1954, to 31st March, 1955. Three years' observations are included for the brine.

The recovery of normal ground temperature at the 3 ft level is shown in Fig. 3. By the middle of August the cooled ground has reached the same temperature as that of ground 30 ft away from the heat-pump grid. These figures were obtained during the third summer after the grid itself was first used. The temperatures in the ground were measured by plastic-insulated copper-Eureka thermo-junctions sealed with bitumen into small stainless-steel cones. These were attached to a rod and driven into the soil to the appropriate depth. The rod was then unscrewed, leaving the steel cone in the ground with the plastic surface of the wire in contact with the soil up to the point where it emerged from the surface. This procedure removed any danger of conduction of heat down supporting rods or tubes to the thermo-junction.

The ground over the buried tank has been sown each year with root crops. The grid, as mentioned earlier, lies under a lawn.

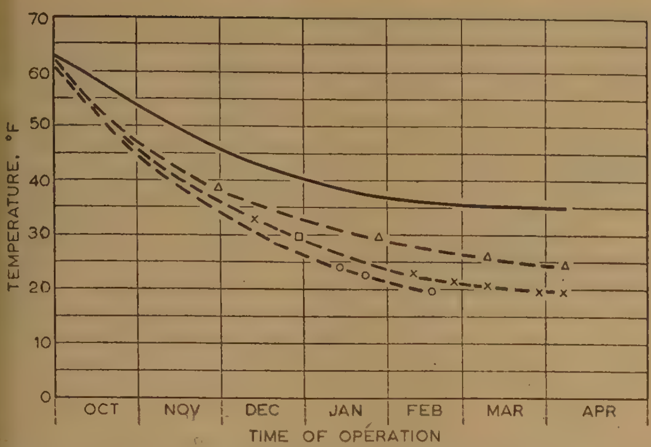

Fig. 2.—Variation of brine temperature with length of time of operation of heat pump (taken at evaporator).

—— Undisturbed ground at 3 ft depth 30 ft from heat-pump grid 1954–55. The curve is smoothed.

Brine temperatures

△ 1951–52
□ 1953–54
× 1954–55
○ 1955–56

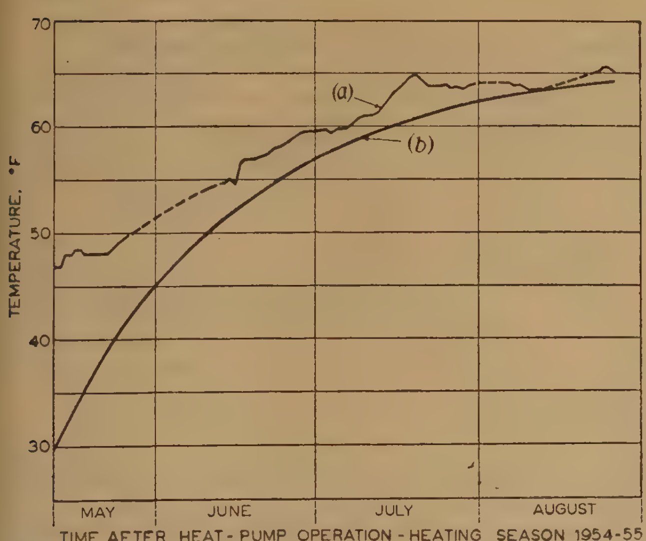

Fig. 3.—Summer recovery of ground temperature after cooling by heat pump.

(*a*) Temperature 3 ft down in undisturbed ground.
(*b*) Ground temperature 1 in from heat-pump cooling pipe. Depth: 3 ft.

No deleterious effect of the cooling on plant growth has been observed in either place, but the surface of the lawn becomes somewhat convex by the end of February.

(6.6) Observations on the Performance of the Shinfield Heat Pump.

During the periods of operation from 1951 until February, 1956, the heat pump has operated under each of the following conditions for various lengths of time:

(*a*) Maximum source temperature (beginning of heating season).
Low demand for heat (high external ambient temperature).
Optimum conditions in heat-pump circuit, i.e. clean heat-exchanger surfaces, proper refrigerant charge, optimum thermodynamic conditions.

(*b*) Minimum source temperature (asymptotic value).
Low demand for heat (high external ambient temperature—end of heating season).
Optimum conditions in heat-pump circuit.

(*c*) Maximum source temperature (artificially contrived for short period in 1951).
High demand for heat.
Optimum conditions in heat-pump circuit.

(*d*) Minimum source temperature (asymptotic value).
High demand for heat.
Optimum conditions in heat-pump circuit.

(6.6.1) Relative Consumption of a Gas Boiler and the Heat Pump.

The daily performance of a heating appliance on a broad basis may be expressed as the ratio of the calculated heat loss per degree Fahrenheit difference of temperature maintained between the inside and outside air temperatures for the heated laboratory to the daily energy consumption expressed in heat units for a similar temperature difference.

The measured rate of heat loss of the laboratory heated by the heat pump was 0·867 kW per deg F difference between the air temperatures. The heat pump could operate daily to heat the laboratory for 12 hours under time-switch control. In addition, it could operate during the night to maintain the temperature in the storage tank. Over 12 hours, the total building heat loss would be 10·4 kWh per deg F difference maintained. The mean daily electrical consumption per deg F difference was computed from observations taken over a period of three years, neglecting those days on which the heat pump was not operating correctly.

The measured rate of heat loss of the gas-heated building was less than that of the building heated by the heat pump. The mean daily consumption of gas in kilowatt-hour equivalents was determined from observations over the same three years as for the heat pump.

The following illustrates the relative performance of the gas boiler and the heat pump obtained as described:

Daily Energy Consumption per degree Fahrenheit Difference Internal-to-External Air Temperature.

Gas-heated laboratory	10·0 kWh (equivalent)
Heat-pump laboratory (corrected to same insulation value)	3·6 kWh
Ratio of gas to heat pump daily consumption (mean taken over 3 years)	3·1

The Overall Performance of the Heat Pump is Calculated as Follows:

Measured daily rate of heat loss of heat-pump laboratory per deg F difference internal to external air temperature maintained (12-hours per day) ..	10·4 kWh
Overall p.e.r. of the heat pump is therefore.. ..	10·4/3·9 or 2·6

(6.6.2) The Monthly Load Factor.

Fig. 4 shows the variation of the monthly load factor (total hours of operation divided by the number of hours in a month) over the heating season, October to April. The individual years showed most variation of the means in November, December and March. The curve is asymmetrical, the hatched area being given to indicate the increase in load factor due to the fall of the p.e.r. in spring as opposed to autumn because of the cumulative fall of the source temperature throughout the year.

(6.6.3) Thermodynamic Performance of the Heat Pump.

Table 2 and Fig. 5 illustrate the thermodynamic performance of the heat-pump circuit and also comparative rates of heat absorption from the ground.

The efficiencies of the condensing heat exchanger and the compressor and motor system agree closely with expected values.

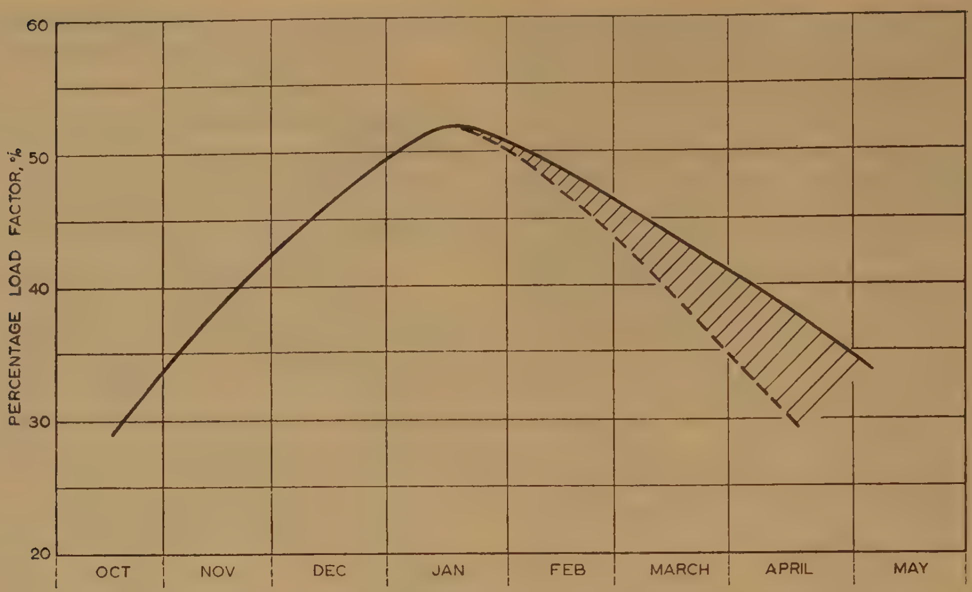

Fig. 4.—Variation of monthly load factor (means of 3 years' observations).
The hatched area shows the effect of the cumulative decrease of source temperature.

Table 2

THERMODYNAMIC PERFORMANCE OF HEAT PUMP AND COLLECTION OF HEAT FROM LOW-GRADE HEAT SOURCE

Rate of heat input to condenser	Rate of heat output to water	Condenser efficiency	Electrical input to compressor	Work done on Freon-12	Efficiency of compressor and motor	Rate of heat input to suction vapour	Heat taken from soil	Heat absorbed from room air†	Contribution of each source of low-grade heat			Temperature of source
									Main tank	Septic tank	Grid	
kW	kW	%	kW	kW	%	kW	kW	kW	kW	kW	kW	deg F
32·1	28·6	89*	7·65	5·60	73*	26·5	22·50	4·0	(m)22·5	—		40
24·7	22·0	89	6·95	5·07	73	18·63	14·13	4·5	(m) 8·53	1·5	4·1	27
28·7	25·5	89	7·57	5·52	73	23·18	18·68	4·5	(e) 11·28	2·0	5·4	25
21·7	19·3	89	7·87	5·75	73	15·95	11·30	4·65	(m) 7·1	1·3	2·9	22

(m) Measured.
(e) Estimated.
* Established for one condition and assumed constant.
† Estimated as difference of columns 7 and 8.

The contribution of each source of low-grade heat to the total absorbed by the evaporator is subject to appreciable error, since the temperature differences involved are small and the difficulties of measurement considerable. The rates of flow to each part of the source have, however, been established with an accuracy of $\pm 2 \cdot 5$ and the totals of the individual contributions when measured separately agree with the total heat given to the evaporator.

The grid under the lawn was the only part of the source for which estimates could be made. The expected rate of output from this was 5 kW, and Table 2 shows that the output obtained was in substantial agreement.

(6.6.4) Maintenance and Attendance.

Maintenance on the heat pump itself has been very slight during the four seasons of operation. Fracture of a faulty valve sealing cap caused considerable loss of refrigerant at the end of the first heating season. Apart from this, occasional small leaks have appeared, but these have been located before any appreciable refrigerant charge has been lost. The flow indicator has, however, needed attention.

The evaporator and condenser have been dismantled and cleaned once earlier in the period. This procedure was repeated in the summer of 1956, the compressor being overhauled at the same time.

Attendance has been limited to a rapid weekly visual inspection for obvious defects. A check for leakages has been made once monthly on the average.

When the system has failed in service it has been due, as described elsewhere, to inadequacy of the source of low-grade heat. The measures taken to combat this have been described elsewhere in the paper.

(7) ECONOMICS IN PRESENT STATE OF DEVELOPMENT

(7.1) Capital and Running Costs

The present capital cost of a vapour-compression heat pump—the only type for which figures are readily available—can be divided into four roughly equal parts:

(i) Compressor and motor, and electrical control gear.
(ii) Low-temperature heat exchanger with pump or fan.
(iii) High-temperature heat exchanger with pump or fan.
(iv) Refrigerant, or working fluid, pipework, expansion valve, safety devices and heat distribution system.

If a heat source, such as a river or a well or the air, is not conveniently available, the cost of well sinking, ground coils or

other alternatives must be added. Costs of heat-pump installations with water or air sources can be estimated from average figures given in the literature. In all known cases, these costs are based on refrigeration practice and hence on a system having a luxury value either as a direct amenity to the consumer or as providing for the preservation of essential materials of high value. Similarly, costs of alternative methods of heating can readily be based on figures obtained from the literature, although these are not always concordant.

Table 3 gives the actual costs of the Shinfield heat pump. Table 4 gives an estimated analysis of the cost of providing space heating for a small commercial building by various methods. Selection amongst these methods will always be influenced by the values attributed to maintenance and attendance.

(7.2) Fuel Efficiency

The overall thermal efficiency of a system terminating in a heat pump is the product of the efficiency of the preceding stages and the p.e.r. of the heat pump. The thermal efficiency of all processes up to power-station terminals in Great Britain is about 24%, and the corresponding figure at the consumers' terminals is slightly lower. Claims are made that solid or oil fuel can provide space heating with a thermal efficiency of over 65%. It is therefore only when the p.e.r. is somewhat greater than 3·5 that any total economy in fuel as compared with solid- or oil-fired devices can be indisputably claimed for the heat pump. For gas, since the production efficiency is about 50%, and the thermal efficiencies of fires and other heating appliances are somewhat below and somewhat above 65% respectively, there is undisputable economy with the heat pump at p.e.r. values in excess of 2. Since the heat pump is more likely than other appliances to yield nearly its claimed efficiency throughout life, it may be credited with an effective fuel economy at values of p.e.r. somewhat less than the figures quoted above. The electrically-driven heat pump provides a real overall fuel economy as compared with direct electrical heating methods at any p.e.r.

Table 3

DISTRIBUTION OF COSTS OF INSTALLING EXPERIMENTAL HEAT PUMP (10 H.P. CAPACITY) AT SHINFIELD IN 1951

Item	Cost
	£
Heat-pump components, local piping and thermal insulation	1 142
Refrigerant	100*
Safety devices	38
Heat source	253†
Brine	85
Radiators and piping for heat-distribution system	234
Labour (includes wiring)	400‡
Total	2 252

* Design of evaporator can be improved to save £40 approximately.
† Inflated by exceptionally rainy conditions.
‡ £60 carriage charges included for buried tank.

(8) FUTURE DEVELOPMENT OF THE HEAT PUMP

Many industrial processes involve the concentration of liquid solutions, either the condensate or the distillate being preserved. These processes can conveniently be carried out by direct compression of the process vapour and by arranging that this vapour condenses in a coil immersed in the concentrating liquid. The small amount of compression required for such a heat-pump system to provide an adequate rise of temperature results in a very high p.e.r., values as high as 20 being achieved in practice.

In many drying processes, both domestic and industrial, it would be possible and economically advantageous to feed the escaping waste heat back into the system with a heat pump, at the same time taking advantage of the latent heat of condensation of the associated water vapour.

Some of these developments are perhaps of no direct interest to the electrical industry, although electric drive may be essential in processes demanding ambient conditions free from fumes.

Some sources of heat are available because large quantities of

Table 4

COMPARATIVE ANNUAL COSTS FOR SPACE HEATING BY VARIOUS METHODS. SMALL COMMERCIAL BUILDING 150 × 10⁶ B.TH.U./ANNUM. (25 kW Output Capacity).

System	Solid fuel boiler	Fuel oil-fired boiler	Gas boiler	Electric tubular heaters	Immersion heater or electrode boiler	Electrically-driven heat pump	
Efficiency	60%	65%	70%	100%	85%	P.E.R. 3	P.E.R.† 4·5
Fuel price	£7 per ton	1s. 2d. per gal	*1s.4d.per therm	1d. per kWh + £6 per kW maximum demand			
Capital cost	£520 with auto-stoker	£520	£450	£200	£450	£1 325	£900
Life of plant	20 years	20 years	20 years	30 years	20 years	20 years	20 years
Percentage capital charges	8	8	8	6·5	8	8	8
Fuel costs—annual ..	£86	£79·5	£143	£327	£359	£109	£72·7
Attendance	£50	£25	£5	£5	£15	£15	£15
Maintenance	£15	£10	£5	£5	£15	£10	£10
Annual capital charges	£41·5	£41·5	£36	£13	£36	£106	£72
Total annual costs ..	£192·5	£156	£189	£350	£425	£240	£169·7
Equivalent annual coal consumption ..	9·35 tons	—	16·3 tons	25·4 tons	30 tons	8·5 tons	5·7 tons

* Cost of gas to Perivale Laboratory.
† Higher-temperature heat source if available.
Interest on capital, 5% per annum.
Cost includes installation in all cases as well as heat-distribution system.
Cost of heat pump does not include for earth source of low-grade heat.

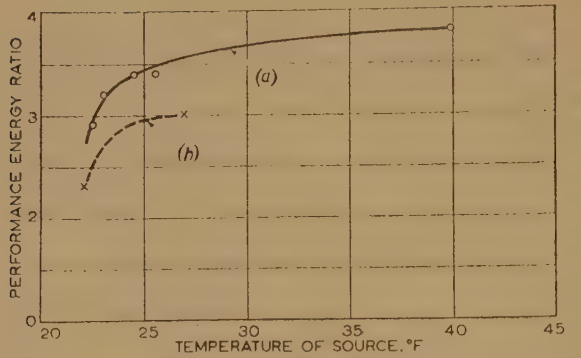

Fig. 5.—Variation of performance energy ratio with source temperature (heat-pump compressor only).

—— Condensing temperature: 116° F.
---- Condensing temperature: 122° F.

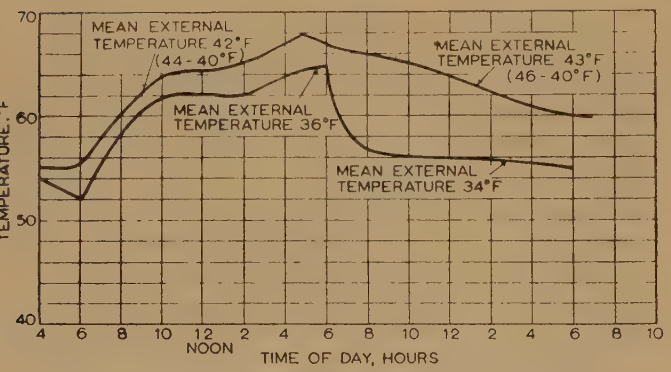

Fig. 6.—Rates of rise and fall of laboratory air temperature.

material must be cooled irrespective of the need for space heating or hot water. Examples are abattoirs, mortuaries and cold stores. Here the capital cost of a heat pump does not enter so largely into the picture, since the low-temperature heat exchanger must in any case exist and the heat can be made available for use by a simple increase in the working pressure and capacity of the compressor.

Dual-purpose applications of the heat pump, such as space-heating in winter with air-cooling in summer, do not appear to have much future in this country, although the possibility exists for cinemas, large office blocks, large stores and hotels. The adaptation of heat pumps driven by fractional-horse-power motors for various domestic and small commercial uses is of interest. Most of these adaptations can be envisaged as playing a dual role, e.g. cooling milk to provide hot water on small farms; cooling domestic larders with and without associated refrigerators to provide domestic hot water; drying clothes either by direct recirculation again over evaporators and condensers or again associated with a refrigerator. Because of this duality of purpose the economics of such small systems become favourable, and the methods should stand or fall only by virtue of their practicability. Larder-cooling water-heating units are at present on the British market.

(9) THE HEAT PUMP AS AN ELECTRICAL LOAD

A direct space-heating load has certain characteristics which make it unattractive to the supply industry, but if space heating by electrical means is to be provided, the heat pump enables it to be done with less disturbance to the supply.

Also, with present techniques, the construction of the heat-pump system provides a certain amount of thermal storage, and this in itself tends towards a better load factor. The introduction of external thermal-storage arrangements into the system is very favourable since it reduces the size of plant required for any given varying heat load and thus, owing to the high capital cost, results in a big advantage.

Economy to the domestic consumer would perhaps suggest the use of base-load space-heating by means of the heat pump with peaks met by local portable electric fires. This tendency may increase to undesirable limits if attempts at economy by close design of an installation lead to underestimation of capacity.

Any development of dual-purpose units is likely to lead to improvement in load factor.

An aspect which requires consideration is that the proposed load is a motor load and possibly can most economically be met by making 3-phase supply available at residential premises. With small installations the cheapest form of control is likely to be by on-off switching, and with single-phase motors, starting currents may then be a problem. In larger schemes where continuous control, e.g. by control of the rate of flow of refrigerant is adopted, operation at a fraction of rated output may give rise to poor power factors. This condition can be ameliorated by the use of multiple units, but only by accepting greater cost.

(10) UTILIZATION OF WASTE HEAT FROM POWER STATIONS

The heat pump is the only method of recouping some of the losses from the cooling water of existing condensing plant in a steam power station. Discussion of the economics of such large schemes is beyond the scope of the paper. Higher-temperature outputs made possible by the development of improved refrigerants might be a considerable help, however, in furthering the use of the heat pump in district-heating schemes.

(11) THE HEAT PUMP IN RELATION TO THE ELECTRICITY SUPPLY INDUSTRY

On the basis of present costs and having regard to the indeterminate nature of attendance, maintenance and amenity charges, no very strong case can be made out on economic grounds for the wide adoption of the electrically-driven heat pump in preference to all possible competitors. There are undoubtedly very good prospects that capital costs can be reduced, but the extent to which this is possible is speculative. It is nevertheless undeniable that there is a very strong popular demand for heating by means other than solid fuel, which is met by fuel oil, gas, and direct electrical methods.

There are obvious reasons why the use of imported fuel oil is to be discouraged in the national interest, and there are considerable areas in which gas supplies are not available and in which electrical power is the only alternative to solid or oil fuel. Even at the present cost, the advantage of the heat pump over direct electrical methods appears clear. The electricity supply industry is therefore well justified in taking steps to develop methods which should enable consumers in rural areas to obtain power for heating purposes at reduced cost.

(12) CONCLUSIONS

Reliable evidence exists that small heat pumps (up to 7·5 kW input) can be manufactured to give p.e.r.'s of 3 with natural heat sources, provided that the output temperature does not exceed 130° F. With waste-heat sources at 80° F p.e.r.'s of 5 are to be expected. Under comparable conditions, somewhat higher ratios may be expected with larger units.

The heat pump saves fuel in appropriate circumstances but

involves higher capital cost than other apparatus for the production of heat. It thus shows up favourably when heating at high load factors is to be provided, or when a non-basic fuel must in any case be used.

Heat pumps in the present stage of development are only competitive with non-electrical methods provided that proper account is taken of attendance, maintenance and amenity charges.

There exists a clear justification for the electricity supply industry to develop the heat pump to satisfy the large popular demand for a form of heating which does not make use of solid or imported liquid fuel, in areas where electricity is the only alternative. If such development should result in a considerable reduction of capital costs, the field of successful competition would be greatly widened.

In the domestic field, fractional-horse-power units show the greatest promise of early successful application. Although further study is needed, there is a strong possibility that high capital costs can be discounted by the development of dual-purpose equipment.

The capital costs of heat pumps for space-heating are inflated if it is necessary to cater for infrequent short spells of extreme cold. This could be met by the development and use of cheap methods of thermal storage especially adapted to the low-temperature characteristics of the heat pump.

The application of the heat pump to suitable industrial processes, such as drying or evaporation, offers great economy in production costs; e.g. in the evaporation of water, the total cost per ton evaporated by the use of a heat pump may be one-quarter of that by straightforward evaporation. Such applications are of far more importance to the user than to the electricity supply industry, but should be encouraged since increase of knowledge and experience of the art should aid development in fields in which there is more direct interest.

Electric motors are in many cases the only possible drive for a heat pump. When, as in some of the larger applications, they are in competition with other forms of drive, they suffer from the disadvantage of not allowing waste heat from power production to be directly recovered as in the case of engines operating on basic fuels.

Whether or not there is an energetic attack on the development of the heat pump in the low-capacity range—a field which is of the greatest potential interest to the supply and manufacturing sides of the electrical industry—advance in this field will be aided by developments in the higher-capacity range where particularly favourable sources may exist and where schemes are large enough to bear the cost of detailed examination. Expenditure on such schemes, even above that economically justifiable, can therefore provide large contributions to general future developments.

A more complete analysis than the present is hardly possible unless adequate operational trials are carried out in Great Britain. In view of the many factors affecting practical performance, any such schemes should be designed to yield not only heat but also information.

(13) ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of several colleagues in this work, including Mr. H. J. Eighteen, who constructed the heat pump at Shinfield, Mr. T. P. Hughes, who assisted in many of the observations, and the staff at the Shinfield Field Station, who gave invaluable help by taking daily readings of energy consumption.

Thanks are particularly due to Mr. L. Gosland for his advice and suggestions during the preparation of the paper.

The author is further indebted to the Joint Acting Directors of the Electrical Research Association for permission to publish the paper.

DISCUSSION BEFORE THE INSTITUTION, 10TH JANUARY, 1957

Mr. J. A. Sumner: I believe that this is only the second paper on heat pumps to be presented before The Institution. The first was, of course, the paper by Mr. Haldane in 1930.

The author has shown great courage in presenting the paper, bearing in mind all the reasons given in the last decade why the heat pump could not possibly work or be a success.

An adverse criticism of heat pumps is that the maintenance and repair costs would be far too high. When we consider that one organization has recently completed the sale of its millionth heat pump (in the form of a domestic refrigerator) it would not seem that this argument is very strong, or if it is, it certainly does not deter people from buying a machine that upgrades heat.

It has been said that nowadays we cannot afford the capital required to build heat pumps. I understand that the National Coal Board is proposing to spend £1 000 million in the next ten years in order to increase the output of coal by 10 million tons a year. I think it could be demonstrated that, if the N.C.B. were to allocate even £1 million of this to building heat pumps, they could conserve more coal than if it were spent on new plant.

A further argument which has been advanced against the development of heat pumps is that their capital cost is too high. This complaint has not, to my knowledge, been made against the development of refrigeration apparatus, on which industry spends many millions of pounds per year. How can it therefore be said that the capital cost of a heat pump, which refrigerates and produces heat, is too high when the same complaint is not advanced against refrigeration machinery which serves almost exactly the same purpose?

It is difficult to see why the electricity supply industry should object to a device which can produce the equivalent of 10 kW of heat in a house or building with a demand on the supply system of only about 3 kW. The use of the heat pump in place of direct resistance heating would mean that the industry would consume only $\frac{1}{3}$ lb of coal, instead of 1 lb as at present, in order to produce the equivalent of 1 kWh of energy used in space heating.

I would reiterate once again that we are facing a most serious fuel shortage in this country. The danger period will be during the next two or three decades, i.e. before there is time to develop the very welcome atomic-energy programme. Prejudice and blind criticism will always have to give way ultimately to truth, and the stark realities of the fuel shortage—which are only now beginning to dawn upon the great majority of people—must eventually require that the heat pump, and any other means of conserving fuel, be given full support.

Mr. F. W. Skelcher: Section 1 of the paper refers to the direct use of steam in the absorption-type heat pumps. Are such systems in practical use, and if so, can a description be given?

Can the author indicate whether published data are available on research in connection with heat utilization from the soil?

With reference to Section 4, it is appreciated that higher output temperatures can be obtained by feeding waste heat from internal-combustion-engine drives into the system, but will not the heat so utilized be credited to the performance and so raise the overall p.e.r.?*

The author rightly mentions, in Section 6.5.1, the importance of adequate lubrication of the compressor and the effects of deposition of oil on the heat-exchanger surfaces. However, my experience with two installations in the Midlands Division of

* Performance energy ratio.

the Central Electricity Authority indicates that, in large systems, the major troubles are caused through inefficient lubrication, owing to contamination of the oil with refrigerant and moisture which enter the system. I think that more emphasis might have been laid on this aspect.

Has allowance been made for a building to house the solid- and oil-fuel-fired boilers mentioned in Table 4, and could an explanation be given for the variation between the figures of £2 252 for the Shinfield system and £1 325 for the installation quoted in the Table?

A detailed study of the heat pumps in the Midlands Division indicates that a satisfactory comfort level is readily achieved, but great care is needed in designing the distribution system. I welcome the comments in the paper that experience gained in such installations assists in the development of medium-size and small plants.

In view of the widening gap between power demand and natural fuels available in this country, the various fuel-economy advisory committees would do well to pay more attention to the value of heat pumps in the efficient use of our fuel resources.

Dr. J. W. Macfarlane: I am interested in the paper for two major reasons. First, in spite of the large volume of published work on the subject, little attention has been paid to it by the people who could do something to assist our fuel economy in this country, and secondly I have built and experimented with two heat pumps of my own.

I am using the soil as a source of low-grade heat, and have 1 000 ft of pipe. 480 ft of 1 in copper pipe is under my house and I added to this, first in series and now in parallel, 520 ft of 1 in pipe underneath the lawn. There is the possibility of adding a little air heat exchanger in a similar place to the septic-tank heat exchanger shown in the paper. The system has been giving a coefficient of performance of about 3·4 since 1949. I do not know the exact details and so I cannot compare my figures exactly with those of the author, but in general they appear to be very similar.

For the last three years I have had a domestic hot-water heat pump consisting of a $\frac{1}{6}$ h.p. hermetic refrigerator unit taking its low-grade heat from the atmosphere. The coefficient of performance is about 3·9, and it is showing a marked advantage over an immerser, temporarily placed in the same hot-water tank, of nearly 3·1 : 1.

There is a reference to the brine grid under the lawn, and I note with interest that it had a somewhat convex shape in February. It has had a similar effect on my lawn.

My first trouble with the heat pump was a complete and total loss of Freon. It was circulating through the whole system and not using a brine intermediary. The reason for this was traced to a reaction between the soil and the aluminium-bronze coupling and presumably the copper pipe. On examination, there was virtually no sign of the coupling. The new pipes, now in position since 1950, were joined together with brazed brass couplings. I should be interested to know the method used by the author for joining the pipes and whether there has been any trouble.

In Section 7.1 there is a reference to the cost of heat-pump installations. The technical and capital aspect of domestic units has been clouded seriously by purchase tax. We are inclined, in discussing these matters, to consider purely and simply what they cost to make; but the effect of purchase tax must be noted when we sell to the public.

Mr. P. E. Montagnon: In, say, five or ten years' time rising fuel prices may mean that a revision of Table 4 will show the heat pump to great advantage. Research and development must make it ready for use when the time comes.

At present, wherever there may seem to be an economic case for a heat pump the capital expenditure on the plant has to be considered in comparison with other ways of spending the money which might bring in more interest. There is no financial incentive to save the country's fuel.

Suggestions are made in the paper about the ways in which the cost of a heat pump can be reduced, but there are other components of the cost which cannot be reduced and indeed are increasing. I refer to pipework, building foundations, etc. No amount of research on the mechanical side of the plant will correct that.

There is another way of tackling the problem, which makes use of two situations where a heat pump is even now likely to be of real advantage. They are mentioned in the paper, but need to be emphasized. The first is when a refrigerating load is an essential part of whatever process may be concerned. A good example is the large plants where milk is bottled. The combination of the heating and cooling processes can result not only in a substantial reduction in fuel but also in a reduction of the capital cost of the plant involved. The reason is that the refrigerating plant must be there all the time, and a new use is found for the condenser part of the refrigerators.

The other situation where the heat pump could be of great value is for drying processes. Nearly all the heat in the fuel is normally wasted as latent heat in warm moist air. The heat pump cannot perhaps be expected to work at such a high efficiency that no fuel is needed at all, but, at least, it might substantially reduce the consumption. In the process, warm moist air coming out at the far end of the drying machine would be used as a low-grade heat source. The cold end of the heat pump would be placed in this warm moist air and it would condense water from the air. The heat absorbed in that way would be transferred to the fresh air coming into the plant. The heat pump would, in this process, repay its capital cost at a much higher rate than the small percentage on which calculations are usually based.

Mr. B. Donkin: Table 4 would be more instructive if the cost of fuel were given on a common basis. Using the author's figures, the cost per therm is as follows:

Coal	8d.
Oil	$8\frac{1}{2}$d.
Gas	16d.
Electricity	52d.

There is therefore a strong inducement to use coal and oil provided that their utilization is both convenient and efficient.

Table 3 gives the distribution of the capital cost, but does not give any figures for the design costs. I should like to know whether these are included.

Table 4 shows clearly that the high capital cost of the heat pump makes it uneconomic for domestic heating and hot-water supplies with a relatively small annual load factor. It is possible, however, that there may be industrial applications with much higher annual load factors where it could be usefully applied.

The author proposes to use the heat pump for up-grading waste heat from electric power stations, but surely it must be cheaper to extract the heat at the required temperature by bled steam or back-pressure turbines. The recent paper on the Pimlico district heating scheme* has shown that heat can be sent out from the power station at 6d. per therm compared with 15·5d. per therm for overheads, maintenance and attendance only, i.e. excluding fuel cost, for a heat pump with a p.e.r. of 4·5 given in col. 8 of Table 4.

Mr. P. Schiller: The paper makes no direct reference to annual load factor, but gives monthly load factors, which are irrelevant from the viewpoint of electricity-supply economics. Table 4

* DONKIN, B., JOHNSTON, C. M., and OCKENDEN, E.: 'The Pimlico District Heating Undertaking—Costs and Financial Results,' *Proceedings of The Institution of Civil Engineers*, 1956, 5, Part I, p. 323.

however, seems to be based on an annual load factor of 20%. A commercial consumer needing an 8 kW heat pump, as referred to in the Table, is unlikely to be on a maximum-demand tariff. If he is on a floor-area tariff and changes from solid fuel to a heat pump, the additional revenue accruing would be about 1d./kWh, whereas a 20%-load-factor supply would, in the south of the country, cost the Area Board concerned about 1½d./kWh at the bulk-supply point. Adding distribution losses of, say, 10%, this figure increases to 1·65d./kWh, and if a proper share of other distribution costs were added, it could approach 2d./kWh, as against a revenue of 1d./kWh. If the consumer were on a maximum-demand tariff, the position would, of course, be more favourable.

With regard to domestic premises, Mr. Sumner's reference to a possible collective load factor of 36–40% surprises me. From data he has published for his own heat pump, which is combined with floor heating, I arrive at a load factor of only 23%, although substantial thermal-storage capacity is incorporated. Owing to lack of diversity, even large-scale application of heat pumps could not improve this load factor appreciably.

I deprecate the present practice of assessing the economics of the heat pump only on the basis of existing retail tariffs, without regard to the true cost of supply. Any form of on-peak heating is undesirable, unless an economic return can be obtained. I favour a tariff with different day and night rates, the day rate to be much higher than the running charge of present domestic tariffs. This would also enable an attractive differential to be offered for off-peak consumption.

If heat pumps were still an economic proposition at such higher tariff charges, I would welcome this method of on-peak heating.

Mr. J. F. Fletcher: I first became interested in the domestic applications of the heat pump about two years ago when my solid-fuel boiler needed replacement. The only domestic units available at the time used the principle of larder cooling for water heating, but since these appeared inadequate for my requirements, I decided to build a single-purpose heat pump which would use heat from outgoing waste domestic hot water as a source. Actually only the waste water from the bath and basins upstairs is used, which saves the expense of an underground storage tank, and avoids the contamination inherent in kitchen waste.

About one-sixth of my total heat requirements are obtained (second-hand, so to speak) in this way, the remaining part of the heat being extracted from the outside air. By using two solenoid valves and a time switch, the heat pump runs alternately on the air evaporator and the tank evaporator, each defrosting while the other is working.

In the domestic field, running costs for various fuels are given in Table A.

The Table shows that, so far as running costs are concerned, the heat pump with a p.e.r. of 3 or more shows an economy over every other form of fuel.

I should like the author's views on the possibilities of the wider adoption of the principle suggested, namely the re-use of domestic waste heat, and indeed whether there are any further similar installations in this country.

Mr. R. F. Richardson: The last two columns of Table 4 indicate that the capital cost of the heat pump with a p.e.r. of 3 might be £53 per effective kilowatt, whereas Table 3 gives £76 per kW, which seems more reasonable and gives a revised capital cost for Table 4 of £1 900. Such heat pumps should have sufficient associated thermal storage to avoid the primary supply-system peaks, otherwise the inherent load factor of 25% is unattractive.

The cost comparisons with alternative methods do not include off-peak electric floor warming. Such a system, with its low capital cost and off-peak running charge, would present a more attractive alternative to the heat pump. Assuming a capital cost of £15 per kW and an off-peak running charge of 0·9d., the total annual costs would be about £210, compared with direct electric heating at £350 and an adjusted figure for the heat pump (costing £1 900) at £286.

Research work on heat-storage media will be helpful, not only in relation to the heat pump but for other electrical applications relying on heat storage for economical operation.

Experience with field tests on the domestic dual-purpose heat pump for combined larder cooling and water heating has shown a disappointing performance, with p.e.r.'s of about unity. To improve performance there should be a heat leak and some alternative source of low-grade heat for water heating, and the compressor motor should be immersed in the storage tank.

Air-conditioning plant is being installed on an increased scale, and in such cases, by adopting heat-pump principles, heat can be obtained at incremental cost and the capital cost of the plant can be written off against the desired cooling requirements. The aim should be for every air-conditioning plant to be used for cooling in summer and warming in winter.

Mr. R. A. W. Connor: In Section 8 it is stated that the heat pump is of interest for domestic purposes. In spite of the very high price of coal it will be some time before the traditional domestic coal fire disappears, but undoubtedly it will disappear in the ultimate future, and a very big load will then come to the supply industry from heating to higher standards in all applications.

With reference to Section 11, I assume it is intended that consumers in urban areas should get the benefits of heat pumps, as well as those in rural areas.

Capital costs are still very high, but many of the technical difficulties have been overcome. However, a serious non-technical difficulty is that of selling heat pumps to people who use very small quantities of hot water. If the occupier of domestic premises wishes to manage with a very small quantity of heat the case for a heat pump is very difficult to justify. Therefore the first major use of the heat pump in existing premises is likely to be in medium-size and larger domestic

Table A

Fuel	Cost	Calorific value	Theoretical cost per therm	Average appliance efficiency	Net cost per therm
		B.Th.U.	d.	%	d.
Coke	176s./ton	12 500/lb	7·6	40–70	19–10·8
Paraffin	2s. 4d./gal	20 000/pt	17·5	95	18·5
Coal	170s./ton	12 000/lb	7·6	30–40	25·3–19
Gas	1s. 8d./therm	—	20	80	25
Electricity	1d./kWh	—	29·3	100	29·3
				P.E.R.	
Heat pump (electrically operated)	1d./kWh	—	—	3	9·7

buildings. With improved standards of heating, it will eventually be applied to the smaller premises. With regard to new premises, consideration should be given particularly to commercial and larger domestic buildings, where the maximum benefits of the heat pump should be achieved by installing the pump and radiators in the constructional stages.

In Section 12 it is stated that the heat pump should be used not only to supply heat but also information. I would emphasize that the information should not only be accurate but also comprehensive.

Mr. H. I. Scholar: I am more interested in the commercial than the technical aspect of the heat pump, and while travelling in Switzerland a few months ago I read the annual report of the Municipality of Zürich on their heating published in the *Neue Zürcher Zeitung*. To my great surprise I found that the heating was done 1% by electricity, 9·6% by heat pumps and some 73% by coke.

Owing to hydro-electric resources, electricity is much cheaper in Switzerland than anywhere else, and it is to the credit of the heat pump that almost ten times more heat was produced by that means than by electricity. The majority of municipal buildings which are heated in that fashion are either on or near the Limmatquay, the Limmat being the river flowing in this area. For that reason, the installation was first considered, and it was a good investment.

While the Swiss are excellent engineers and always willing to experiment, before a municipality authorizes the expenditure of money it will need to be assured of some return; so this was not a venture undertaken lightly. They must have been satisfied with the first installation to have dropped some of the electrical ones in favour of the heat pump.

Since the night load tariff in Zürich is very cheap and the cost of installation of the heat pumps is very high, the fact that they are installed means a great deal.

I believe that there will at some time be a large export market for heat pumps, and it is quite impossible to build this up without a home market. The reason is that faults in early designs can be easily and fairly cheaply rectified in models delivered to the home market, before any are exported.

Mr. J. A. Feasby: My interest has been largely in larder-cooling and water-heating by heat pumps. I have developed them and produced them commercially. The earlier models made did, in fact, have p.e.r.'s between about 1 and 1·5. The later models have p.e.r.'s between limits of 2 and 3, which was achieved with source temperatures down to 30°F and water temperatures up to about 148°F. However, this was done by recovering the waste heat of the motor-compressor unit. These have efficiencies between about 40 and 50%, and there is obviously much scope for improvement.

The capital costs of heat pumps are undoubtedly rather high, and domestic units feel the effects of purchase tax. Even so, a case can be made out for their fairly high price, and for all-electric houses which have been designed to take them, the saving on approximately £3 000 has been shown* to be £116.

Mr. H. J. Eighteen: Leakage of refrigerant is one of the main problems which have to be overcome in the development of practical heat pumps. The normal flare joint used in the refrigeration industry does not withstand the higher pressures used in heat-pump work, the ¼ in size being the worst offender. At Shinfield an excellent copper-copper joint was used, but unfortunately the manufacturers have decided not to produce any more. Particular care should be taken with valve glands; all valves should be of the packless type, but if these are not available, sealing caps should be fitted.

Components supplied by the refrigeration industry, although very good for their purpose, are not entirely suitable for heat pumps, since they are required to withstand greater pressures. Most troubles have been experienced owing to failures of soft-soldered joints. Although small, these can become rather costly when the charge is lost and the system becomes full of moist air.

Compressor lubrication requires investigation when Freon 12 is used, but the worst case appears during the best conditions for the heat pump, namely when the evaporator is at a higher temperature than the surroundings of the compressor, particularly in a flooded evaporator system.

During the construction of the Shinfield unit no real difficulties were experienced, and except for some initial difficulties with the source, it has given good service.

It is mentioned in the paper that the plant is not reversible. This is so, but it must be remembered that, after the first few weeks of operation, there are a few thousand gallons of brine at approximately 22°F available if a cold store were required. It would be a simple matter to use this, and, of course, it would add to the performance of the heat pump.

Where fans are used with domestic heat pumps care must be taken with their positioning, as they can become objectionable at night if heard in bedrooms. In the larger domestic units, say 1 h.p. and over, anti-vibration mountings should be fitted. There is a strong case for some form of non-metallic flexible coupling to prevent vibration travelling along pipework.

Mr. P. Lewis (*communicated*): If large-scale use of the heat pump can save significant quantities of coal, efforts should be made to persuade the Government to assist with the installation rather than to tax the equipment. Every ton of coal saved from inefficient space-heating methods is better used in electrical power stations and, especially, in the chemical industry.

However romantic the tradition of gazing into the leaping flames of an open fireplace, what the engineer sees is an irreplaceable waste of the nation's resources, thousands of people stifling in recurrent thick 'smog' and an increasing dependence of the country on imported fuels and chemicals.

With their usual production curtailed, there is now a great opportunity for the motor industry to switch to large-scale production of economic heat-pump units.

The new housing plans could then make full use of this clean and labour-saving form of heating—surely a worth-while investment.

[The author's reply to the above discussion will be found on page 276.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 28TH JANUARY, 1957

Cdr. M. B. F. Ranken, R.N. (Ret.): The Germans fitted small heat pumps for air-conditioning in their type 21 submarines, and a number of these were sent to the United Kingdom for experimental purposes. A somewhat similar plant was fitted in the British T class vessel and two slightly larger ones were installed in the latest British submarine. In all these plants the aim was to reduce the battery load to a minimum while submerged, but this may not be a requirement in the future when true submarines are commonplace.

In 1947 the Admiralty decided to investigate the possibilities of a heat pump for the Diesel-driven survey ship, H.M.S. *Vidal*. The plant fitted was designed for a load of 810 000 B.Th.U./h when cooling, and 750 000 B.Th.U./h when heating (p.e.r. of 3·75). The compressor was driven by a 75 h.p. motor and 141 kW were saved compared with direct electric heating.

* *Electrical Times*, 8th November, 1956.

By far the largest heat pump so far installed in a vessel is in the liner *Southern Cross*. The ship is steam-turbine-driven, but for various reasons no steam is available for heating. Power is derived from Diesel-generators, and an air-conditioning plant is fitted which cost no more than 1/15 extra to convert to a heat pump. The cooling load is $8 \cdot 5 \times 10^6$ B.Th.U./h, which requires 760 b.h.p., and the heating load 9×10^6 B.Th.U./h, which requires 955 b.h.p. There is a saving of 69% of power compared with direct electric heating, but it is 20% less efficient than if direct steam heating had been used.

Land plants have included the experimental one built at Norwich at about the end of the recent war. This was followed by specially designed plants at Stourport, Meaford, Cowes and Great Yarmouth. These were all power stations, ranging up to 2×10^6 B.Th.U./h heating load. There was the Festival Hall plant—now replaced for various reasons by a conventional heating plant—and there have been several other smaller installations, but mostly on an experimental basis.

There have been many so-called 'process' plants. For example, one at Grimsby cools well water for ice making, thereby saving about 4×10^6 B.Th.U./h of the main freezing plant's capacity, and at the same time it heats water for thawing the ice to get it out of the cans (heating load, $4 \cdot 4 \times 10^6$ B.Th.U./h). Two ammonia compressors are driven by 180 h.p. motors and a p.e.r. of 4·15 is achieved (Carnot p.e.r., 8·6). A similar plant is understood to be in use at Fleetwood.

Perhaps the most interesting 'process' plants are those designed for the distillation of water. These have been developed from the 2 gal/h plant captured in the U-570 (later H.M.S. *Graph*) and can now handle 15 gal/h for submarines and 25 tons/day for Diesel-driven surface ships. The latter can show a p.e.r. of 14 compared with direct electric heating.

The figures given in Table 1 for p.e.r. achieved are perhaps somewhat higher than could be expected in continuous operation, taking into account heat-exchanger fouling and the like. In Section 6.5.2 the statement that high heating loads are, to some extent, offset by lower condensing temperatures may be true for cooling soil, but there will be a corresponding drop in evaporating temperature when cooling air or some other media which will counteract any temporary improvement in performance. In fact, the temperature range, and hence the load, are greatest under the most extreme conditions, and thermal storage is only a legitimate palliative in suitable applications.

It is most important to view the figures in Table 4 with great caution, since so much depends on the individual application. In general, small heat pumps are only attractive from the economy point of view where there is a corresponding refrigeration requirement, e.g. on dairy farms, but they can seldom compete with direct heating except where electric power is the only available alternative. It is possible that they will become more attractive with rising fuel costs, but there must be a lower limit of size below which they are uneconomic. Even the larger plants cannot compete with direct steam heating or the like, unless there is also a cooling requirement, and this condition seems likely to continue.

The internal-combustion-engine-driven plant with waste-heat utilization is attractive, and much might be done to improve exhaust-gas heat exchangers, but many additional maintenance problems are introduced to offset the possible gains.

Steam-jet vacuum plants are grossly inefficient and wasteful of steam and will be superseded for most applications, but absorption, and eventually thermo-electric systems, require analysis to discover their potentialities in this field.

[The author's reply to the above discussion will be found overleaf.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 5TH FEBRUARY, 1957

Mr. F. Mather: It is unfortunate that, having become accustomed to the term 'coefficient of performance', we now have to think of 'performance energy ratio'.

Reference is made to the heat loss from urban substations, and it would be interesting to know whether the author has any practical suggestions for recovering this without excessive capital expenditure.

The use of the soil as a heat source appears to require extensive underground pipe systems, and it is probable that corrosion would become a serious problem in many places.

In Table 1 it seems unlikely that air at as low a temperature as 90–100° F would be very satisfactory as a medium for heat distribution, despite the fact that it gives a relatively high p.e.r. In the same Table, the figures of 14·1 and 6·0 for possible and achieved p.e.r., respectively, are disappointing. In fact, one of the main obstacles to the use of heat pumps in industry appears to be the difficulty of ensuring that the ultimate performance will justify the high capital cost.

It would be of interest to know whether the popularity of the heat pump in America is solely due to the need for cooling in the summer as well as heating in the winter.

Mr. J. A. Feasby: If the heat pump is to be a successful commercial proposition the following points should be borne in mind:

(i) In order to reduce cost, the mass production of a standard design which can be completely assembled in the factory is essential.

(ii) In order to justify the high capital cost of the equipment the maximum use must be made of the machine, and both the heating and cooling side of the cycle must be utilized, preferably simultaneously and throughout the year.

The above requirements only seem to be met by a small larder-cooling water-heating machine. In the development of these units several problems must be overcome by means of compromise if the capital cost is to be kept to a minimum. The first is that the maximum high-side temperature will be in the region of 140° F in order to give satisfactory hot-water service. To obtain a reasonable p.e.r., a temperature difference of about 100° F is the maximum permissible between the heat source and the heat sink. This means that the larder air temperature will be in the region of 50° F, with the minimum possible temperature difference between the air and the refrigerant, i.e. refrigerant temperatures above 30° F. A temperature of 0° F is desirable for rapid ice-making. To reconcile these conflicting requirements, one machine in current production uses a blown evaporator for larder cooling and switches the fan off to make ice.

Several reasons make it necessary to separate the functions of water heating and hot-water storage. The dimensions of the unit must be kept to a minimum, both to reduce cost and purchase tax, and also to leave some room in the larder for shelves.

If really accurate control of larder temperature is required, an elaborate heat leak and control system is required. However, for normal domestic use, by suitably adjusting the insulation on the hot-water storage tank satisfactory control of larder temperature can be achieved.

Mr. L. F. Napper: In connection with the domestic application of the heat pump located in a larder as a larder-cooling water-heating unit, since the heat input to the larder will, in general, be largely from the kitchen, and since, also, the kitchen is frequently occupied for a reasonable part of the day, an element

of running cost should be set against the heat pump to take account of the additional space heating required to maintain conditions of comfort in the kitchen.

Mr. J. G. Jones: In my experience of heat pumps the electrical industry is interested in putting forward schemes, but unfortunately the high capital cost of the plant invariably stops further development.

However, an air-conditioning equipment, recently installed in a small restaurant, uses a $7\frac{1}{2}$ h.p. condensing unit with shell and tube water-cooling condenser, the water to the condenser being supplied from the mains at approximately 60° F. By restricting the flow through the condenser, this is raised to 90° F, so that 300 gal of water per hour is available for domestic supplies and a laundry, the temperature being raised from 90° F by means of electric heaters. The approximate initial cost of the plant was £1 500.

The author detailed difficulties due to ice formation around the pipes of the evaporator in the ground during winter conditions, and I understand that, in the United States during extreme conditions, electric heaters have been plunged into the ground to provide a source of heat.

Mr. A. Ward: As a power-station engineer I am particularly interested in the use of waste heat, particularly that from the turbine, and the means of transferring it back to the normal feed-water system. Could the author inform us whether any major developments have taken place with regard to this heat transfer?

I am at present carrying out tests on a domestic heat pump for the Area Board. A recent article* described the various means of heating 240 gal of water to a temperature of 140° F. The cheapest means was that of solid fuel which, based on the prices in Manchester, cost 4s. 6d. per week. Using an average reading for the larder-cooling water-heating unit, my costs have been somewhat lower and can be taken as 4s. 1d. per week. This does not, of course, take into account capital charges or the energy used on the apparatus to cool 40 ft^3 of useful pantry space, which acts as a cold room. If the latter was taken into account the cost of heating water would be nearer 3s. 6d. per week.

The efficiency of this type of equipment is not presented in the usual way as 'work done divided by the energy required to do it'. Why is the term 'performance energy ratio' used as a notation for the efficiency, and how can it be related to the normal terms of efficiency?

AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Miss M. V. Griffith (*in reply*): I should like to pay tribute to Mr. Sumner's untiring enthusiasm for the heat pump. His experimental project at Norwich is the symbol of British interest in the subject all over the world. It is disappointing that Mr. Haldane, who installed an earlier if smaller unit and who was the motive power behind the formation of the E.R.A. sub-committee on heat pumps, is unable to be present.

Mr. Skelcher speaks with the authority of the man responsible for the operation of three major heat-pump projects in the country; those at Stourport and Meaford generating stations. We have been associated with him in testing these installations and appreciate his emphasis on the importance of adequate lubrication arrangements. Considered apart from any aspect of comparative fuel economy, the heat pumps in British generating stations are affording valuable practice in the use of high-temperature waste-heat sources (70–80° F), under almost laboratory conditions of observation and the care of skilled engineers. The output capacity of each of these heat pumps is some five times that of the Shinfield installation. The lubrication troubles, which have been so much more pronounced with the larger units, are associated with the high-temperature source and the increased capacity. The smaller Shinfield compressor has splash lubrication, and the dilution of the oil by dissolved refrigerant does not matter. With the warm heat source, migration of liquid refrigerant to the crankcase, which becomes cooler than the evaporator, takes place during the prolonged periods of shut-down which occur in warmer weather. Heating the crankcase should assist in preventing this trouble, but the main requirement is a really leakproof solenoid valve and a non-return valve which remains tight with a low pressure difference across it.

The deleterious effects of moisture in heat-pump systems, particularly if methyl chloride is used as the refrigerant, should be stressed. The entrance of moisture through leaks or during maintenance can be avoided; if not, there will be trouble with bearings and seals and also with the oil, which may become gummy.

The absorption heat pump will not, in itself, have such a high coefficient of performance as the vapour-compression type, but it offers great fuel economy when a certain quantity of steam, and considerable waste water, at say 80° F, exist together. There is a large installation at the Claridge hotel in Paris, and the process is to be examined very shortly by the E.R.A.

The heat transfer from various soils for heat-pump use is described in several United States, Canadian, and E.R.A. reports.

The use of engine waste heat does effectively raise the p.e.r. for a given output temperature as Mr. Skelcher suggests. For instance, a flow temperature of 160° F may be obtained for an effective p.e.r. of 3·3 instead of 2·5, with a source at 40° F. On the other hand, the return water must be cool enough to enter the heat-pump condenser at the appropriate temperature. In view of the latter, it may be worth considering using the waste heat to increase the source temperature instead.

It is difficult to give an accurate figure for the capital cost of a heat pump. The cost of all machinery has risen by some 75% since 1951. Table 3, however, does not purport to give representative costs for a heat pump similar to that installed at Shinfield. The difference between the actual and the estimated costs in Table 4 is due to the special nature of certain of the components and includes a heavy labour charge owing to catastrophic weather conditions during the preparation of the ground heat source. Table B gives an alternative to Table 4, based on more recent estimates and experience.

Mr. Macfarlane gives some encouraging results for his own heat pump. As he does not mention any trouble he has had with the foundations of his house owing to pipes under the cellar floor, I assume this may be taken as evidence to refute those who object to this practice because of the mechanical disturbance which may occur. He does not state whether there was any sign of frost heave in the floor. The high p.e.r. obtained with the heat-pump water-heater suggests that this applies to a heating cycle only and does not include standby losses during continuous operation.

With regard to corrosion of underground pipework, I can only state that, up to the present, we have had no trouble. At Shinfield we use galvanized-iron pipes with screwed connectors.

Mr. Montagnon adds valuable weight to the paper in his emphasis on the use of the heat pump for appropriate dual purposes. The E.R.A. has kept this aspect well in mind in the extensive range of contacts made with potential users of the heat pump. The increase in building costs surely is somewhat in favour of the heat pump in comparison with solid fuel or other

* *Builder*, 14th September, 1956, p. 454.

Table B

ESTIMATED COSTS FOR RANGE OF HEATING SYSTEMS FOR HYPOTHETICAL INDUSTRIAL BUILDING VOLUME: 322 755 FT³
INSTALLED LOAD: 242 KW

Cost item	Auto-fired boiler	Oil-fired boiler	Heat pump		Direct electric	Electrode boiler with thermal storage	Floor warming (embedded cables)
			P.E.R. 3·5	P.E.R. 5			
Capital costs including heat distribution systems	£ 6 000	£ 6 000	£ 18 500* 13 200	£ 14 300* 8 950	£ 3 900	£ 8 000	£ 4 900
Cost per useful kW installed	24·8	24·8	76·5 54·5	59·2 37·0	16	33	20
Annual capital charges at 7%	420	420	1 295 924	1 001 627	273	560	343
Maintenance and repairs	100	70	100	100	30	50	15
Continuous operating attendance ..	300†	100	25	25	15	70	15
Running cost of electricity at 1d./kWh	20	48	880	630	2 680	3 220	3 260
Addition for maximum demand at £6·3/kW and service charges	10	25	441	305	1 525	Off peak	Off peak
Cost of fuel per kWh	£6·5/ton	1s. 2d./gal	—	—	—	—	—
Total fuel costs	930	1 155	1 321	935	4 205	3 220	3 260
Total costs per annum	1 750	1 745	2 741 2 370	2 061 1 687	4 523	3 900	3 633
Annual cost per kW installed	7·23	7·22	11·3* 9·8	8·52* 6·96	18·7	16·1	15

* Prices taken from actual 1955 quotations showing variation.
† Ash removal, fuel-movement, etc.

alternatives requiring large boiler houses. The justification for at least one heat-pump installation has been the saving in costs for boiler foundations in somewhat difficult circumstances.

Mr. Donkin quotes a comparison with the Pimlico district-heating scheme. The cost given for the heat pump includes a heat distribution system, so that, in any case, the comparative figure should be 10d. per therm, since this is given in the Reference as the cost to the consumer at Pimlico.

The paper refers to heat pumps in generating stations only in passing, but the claim that the heat pump is a method of reclaiming losses which involves the minimum of disturbance to an existing station can be substantiated.

Mr. Schiller plays his usual valuable role in keeping our feet on the ground. I would point out, however, that my table of monthly load factors was given to illustrate the variation of demand with average climatic conditions in Great Britain. This aspect is important in design when considering the flexibility of an installation, e.g. the provision of several small compressors instead of one large one. The heat pump, even with a low annual load factor, surely is an amelioration of the effect of direct electric heating with the same load factor, because of its inherent load-reducing characteristics for the same heating requirement. Off-peak operation should be possible with thermal storage, and experiments are being conducted to establish this, since there are certain special problems. Continuous operation with higher day tariffs would surely favour the heat pump, in comparison with direct electric heating, and from the point of view of the supply industry this would seem to be of major importance. The saving in basic fuel is clear in any case from Table 4.

Mr. Fletcher has made a very useful experiment on the use of domestic waste heat, which has been repeatedly advocated but not otherwise implemented so far as my information goes.

Mr. Richardson would like floor warming to be included, and the calculations he gives support this contention. The price he suggests for a heat pump with a p.e.r. of 3 contains the cost of an associated floor-warming installation using the hot-water output of the heat pump. If the thermal storage thus available is utilized by operation in off-peak periods only, £60 can be subtracted from his figure of £286, giving £226 in comparison with £210 for direct electric floor heating.

In reply to Mr. Connor, the rural consumer in Section 11 is selected as being potentially a more favourable heat-pump user because electricity would, in any case, be required for lighting and power, and it would seem undesirable to duplicate utilities in such cases.

Messrs. Scholar and Feasby point out the commercial opportunities for the heat pump. The E.R.A. has always advocated the recovery of motor losses by immersion of the compressor in larder-cooling water-heating heat pumps. Sealing of motor leads has presented some difficulty in the laboratory, but should not be a problem with purpose-made compressors.

Mr. Eighteen emphasizes some points which have arisen in the study of test installations.

Mr. Lewis stresses the saving in coal obtained by the use of the heat pump. As Mr. Montagnon points out, there is an incentive, at present, to save capital rather than fuel, but in the limit this is likely to prove a short-sighted approach to the problem.

As Mr. Mather states, it is unfortunate that people have become accustomed to the term 'coefficient of performance' applied to the heat pump. Since the machine is essentially the

same as a refrigerator, it is not desirable to use the same name for two different relationships.

The cooling of substations by means of the heat pump is under consideration and should prove economic if the heat can be sold. The subject of corrosion in soils has also received a great deal of study, and any difficulties involved should not be insuperable.

I am a little surprised that Mr. Mather considers 90–100° a low temperature for air heating, as this is the design temperature for many systems.

Mr. Feasby makes two salient points on the subject of the larder heat pump. So far as domestic heating is concerned, mass production seems to be essential, and it is certainly important to install heat pumps where the maximum advantage will be obtained from their characteristics.

Messrs. Napper and Jones bring forward points of interest. Mr. Ward asks about the use of turbine waste heat. This is, of course, used for office heating by means of the heat pump, but its use for feed-water heating in power stations has not been tried, so far as I know.

The term 'efficiency' is usually taken to indicate the approach of any process to ideal operation, and therefore cannot exceed 100%. The p.e.r. is the inverse of the efficiency of a heat engine.

Cdr. Ranken supplies some very interesting information on heat-pump applications, and it is hoped that his special knowledge will contrive to be applied sympathetically to the further exploitation of the heat-pump principle. Consideration is being given from the research angle to the potentialities of the absorption and Peltier systems of cooling for heat-pump purposes.

DISCUSSION ON 'THE MEASUREMENT OF STEAM TEMPERATURES IN POWER STATIONS'*

NORTH-WESTERN SUPPLY GROUP, AT MANCHESTER, 27TH NOVEMBER, 1956

Mr. W. J. Thomas: The steam conditions at Deptford West of 400 lb/in^2 at 775° F are much lower than those being used in the construction of to-day's power stations, but the general conclusions reached in the paper I am sure will be valid nevertheless.

Section 7 lays down a code of good practice in the installation of a measuring point in a steam pipe. If these basic rules are combined with the 30-diameter recommendation, test engineers should have no trouble in the assessment of performance of boilers and turbo-alternators.

In turbine testing, an accurate assessment of the steam temperature at the stop valve is a most important item, as an error of 10° F in this figure will result in the steam consumption being approximately 1% in error. The paper shows that, except for the steam-velocity effect, conduction, radiation and contact factors tend to give a low temperature; an error of 10° F low therefore produces a steam consumption which is 1% low. As the tolerance on an acceptance test is $\pm 2\frac{1}{2}\%$, a machine which in fact would be contractually unacceptable could, if such an error was involved, appear to meet its guarantee if it was a borderline case.

I would recommend all those responsible for installing temperature pockets in power station plants to note the findings of the authors on the position of the pockets after steam junctions, i.e. that at least 30 diameters after the junction is necessary for mixing to take place. On a boiler plant recently tested, the steam leaving the two superheater outlets varied by 62° F; the mixture point on which the automatic control operated was at the T-junction itself and showed a temperature equal to one side rather than a mixture temperature. This final point, which was to be moved on later boilers in any case, has now been installed following the recommendations of the authors.

It is interesting to note that during their research the authors have found that the practice of filling the pockets with a material appropriate to the temperature is unnecessary, it being found sufficient to have a long pocket and to hinder the convection currents by using an asbestos plug. I would be interested to know whether a plug in the neck of the pocket or a spiral between the pocket and thermocouple was used.

In Section 7 the pocket in which the thermometer is to be placed comes in for a good deal of attention and we are recommended to have pockets of:

(a) Long length.
(b) Small cross-sectional area.
(c) High thermal resistance.
(d) Small diameter.
(e) Low emissivity.
(f) Low heat capacity.

It appears that the use of thermometers immersed directly in the steam satisfies most of these requirements.

The high temperatures the future must hold to enable progress to be made make the absolute measurement of steam temperature essential if we are to control the temperature to limit the creep which an extra 50° for a short period will give. The paper acknowledges the additional difficulty and risk involved, but I am sure these will be overcome before the need for this type of measurement is made urgent.

The paper will no doubt stimulate discussion on the relative merits of thermocouples against resistance elements for the measurement of steam temperature. For test work where portable robust equipment is required I think the thermocouple is the best proposition. With resistance elements the contact resistance at various joints makes the assembly of the apparatus practically a surgical operation as far as cleanliness is concerned: experience has also shown that when in constant use such elements lose their calibration easily. The use of thermocouples of fairly short length with homogeneous wire from the high-temperature point to the cold junction and the use of copper leads from the cold junction to the measuring instrument have proved very successful. Although not of such high inherent accuracy as the resistance element, for practical work the thermocouple is more than holding its own.

Mr. J. Whitfield: Factors which at first sight appear to present serious sources of error in temperature measurement can be largely eliminated by common-sense precautions. If the authors' recommendations are carried out, readings with 0·1% of the true figure can be expected, but I suggest that there are practical difficulties in measuring to this accuracy.

Resistance thermometers do not appear to be generally acceptable for temperatures above 900° F. Commercial materials generally available are also not ideal. In the case of chromel-alumel, the alumel can be considered as non-homogeneous, causing instability at low and high temperatures. If we resort to iron-constantan we find that the iron is subject to rusting, giving parasitic electromotive forces. Platinum-rhodium is an expensive thermocouple; the e.m.f. developed is small and commercial potentiometers are not generally sufficiently sensitive to give the accuracy required.

The thermocouples used by the authors in the practical work

* Lucas, D. H., and Peplow, M. E.: Paper No. 1872 S, June, 1955 (see 103, Part A, p. 153).

described in Section 8 do not appear to be of high accuracy. The theoretical and practical findings presented by the authors are in good agreement but do not fall into line with similar testing carried out at the Trafford Power Station. In this work the apparatus used was in my opinion ideally suited to this type of measurement.

This work was done with the same intention as that undertaken by the authors, i.e. to measure the temperature gradient across a pipe fed from separate boilers.

The plant comprised two 150×10^3 lb/h boilers generating steam at 425 lb/in^2 and 825° F connected to a steam receiver from which a single 14 in pipe was led off to a 30 MW turbine. The pipe was cut so that a 2 ft test length could be inserted, this test length having already been fitted with instantaneous-response thermocouples fitted in an aerofoil assembly. The position chosen was such that there was at least 50 diameters of single pipe before the test piece. The steam velocity was about 95 ft/s.

Steam temperature control on the boilers is by means of attemperators fitted between the primary and secondary superheaters; during the test the temperatures were varied by altering the setting of the attemperators, the maximum difference being of the order of 100° F.

The work has not yet been completed, but sufficient information has been obtained to show temperature gradients higher than those suggested by the authors.

Mr. C. F. Smith: My colleagues and I have carried out tests on the stratification of superheated steam which follow basically the same line as the authors' investigations at Deptford, but vary in method of measurement and results. Mr. Whitfield has outlined the test layout, showing that the test thermocouples are measuring steam temperature approximately 50 diameters from the mixing point.

The test insert houses two aerofoils each containing 7 thermocouples protruding from the leading edge (see Fig. A). The thermocouple hot junction is of small mass (approximately 0·040 in in diameter) and of instantaneous response. It is in direct contact with the steam and insulated from the body of the aerofoil housing. The N.P.L. calibrated thermocouples are made from 25 s.w.g. wire of 90% Ni 10% Cr, 55% Cu 45% Ni and were check-tested in a sulphur bath showing differences of less than $\frac{1}{4}$° F.

It should be noted that the end thermocouple of each aerofoil, positioned $\frac{3}{8}$ in from the pipe wall, bears out the rule that a thermocouple is free from gradient effect if immersed more than 8 wire diameters in the medium being measured, and that exponential gradients are applicable only for thermometers immersed in pockets.

The examples of temperature profiles shown in Fig. B are typical of the hundreds obtained under varying boiler conditions.

Investigations are now proceeding, using a completely different technique.

Mr. J. R. Appleton: I agree that a 3 in thermo-pocket is sufficient, provided that precautions as indicated in the paper are observed. Lagging is often not concentric on horizontal pipes and round test pockets it is frequently damaged: I suggest that an asbestos tube built in the lagging would reduce damage. In practice, disputes on the steam temperature error are concerned with several degrees, and the paper is timely in showing the magnitude of the various sources of error. It would have been better, however, if the practical tests had been conducted with the higher temperatures now in use.

Mr. H. A. Kirby: In Section 7, there appears a useful tabulation of features which will tend to minimize errors in temperature measurement. This seems to emphasize the inherent difficulty of good design of temperature measuring points, particularly for use in power stations, since the requirements for accuracy are

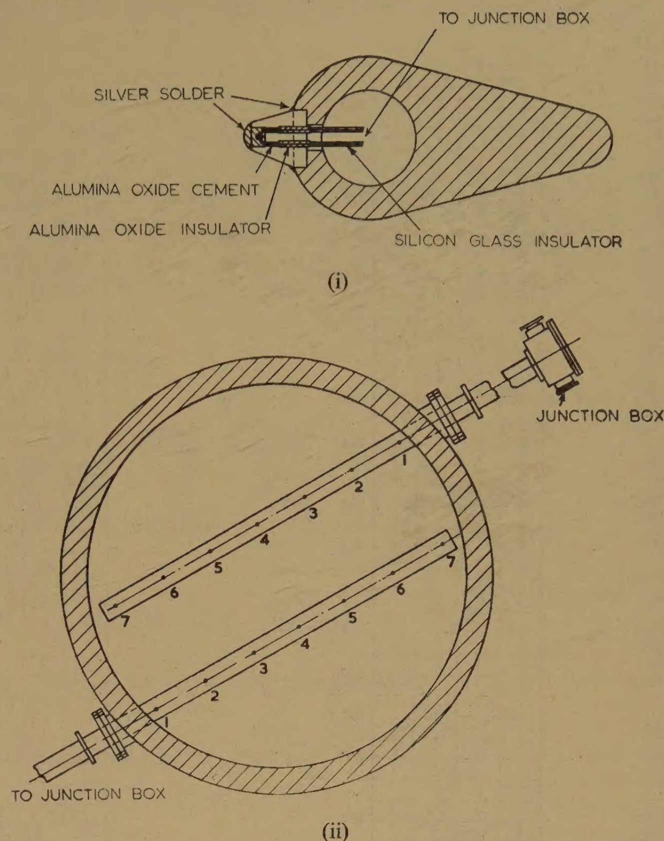

Fig. A.—Test arrangement of thermocouples.
(i) Section of instantaneous-response thermocouple.
(ii) Arrangement of thermocouples in pipe.

almost exactly opposed to the requirements for the structural aspect of the design. Pockets must be short and of fairly substantial cross-section; they must also have a natural frequency of vibration well removed from that of any external impulse likely to be encountered. Thus the equipment which will be installed in practice at the present time is likely to suffer many of the causes of inaccuracy listed in the paper. There is no suggestion that the equipment used at Deptford can be permanently installed, so the experiments, upon which the authors are to be congratulated, must be regarded as an attempt to achieve an ideal under semi-laboratory conditions.

As the authors have indicated, an important function of the measuring apparatus is that of ensuring that safe temperature limits are not exceeded. Margins available to the designer decrease rapidly at high temperatures, so that design stresses have frequently to approach closely the permissible limit. This permissible limit depends on the design temperature, which should take into account the instrument error. As the design temperature rises, so metal thicknesses increase, making rapid starting more difficult. It is, therefore, becoming increasingly important to know the accuracy of the temperature-measuring instruments in permanent installations, and the constancy of that accuracy over a long period of service. The development of better permanent instruments is of equal importance.

The authors conclude that steam flowing in a pipe from two independent sources will be thoroughly mixed in about 30 diameters. This was undoubtedly true at Deptford, yet observations during turbine tests on a large number of installations have suggested—but not in themselves proved conclusively—that steam frequently does not mix over much longer distances.

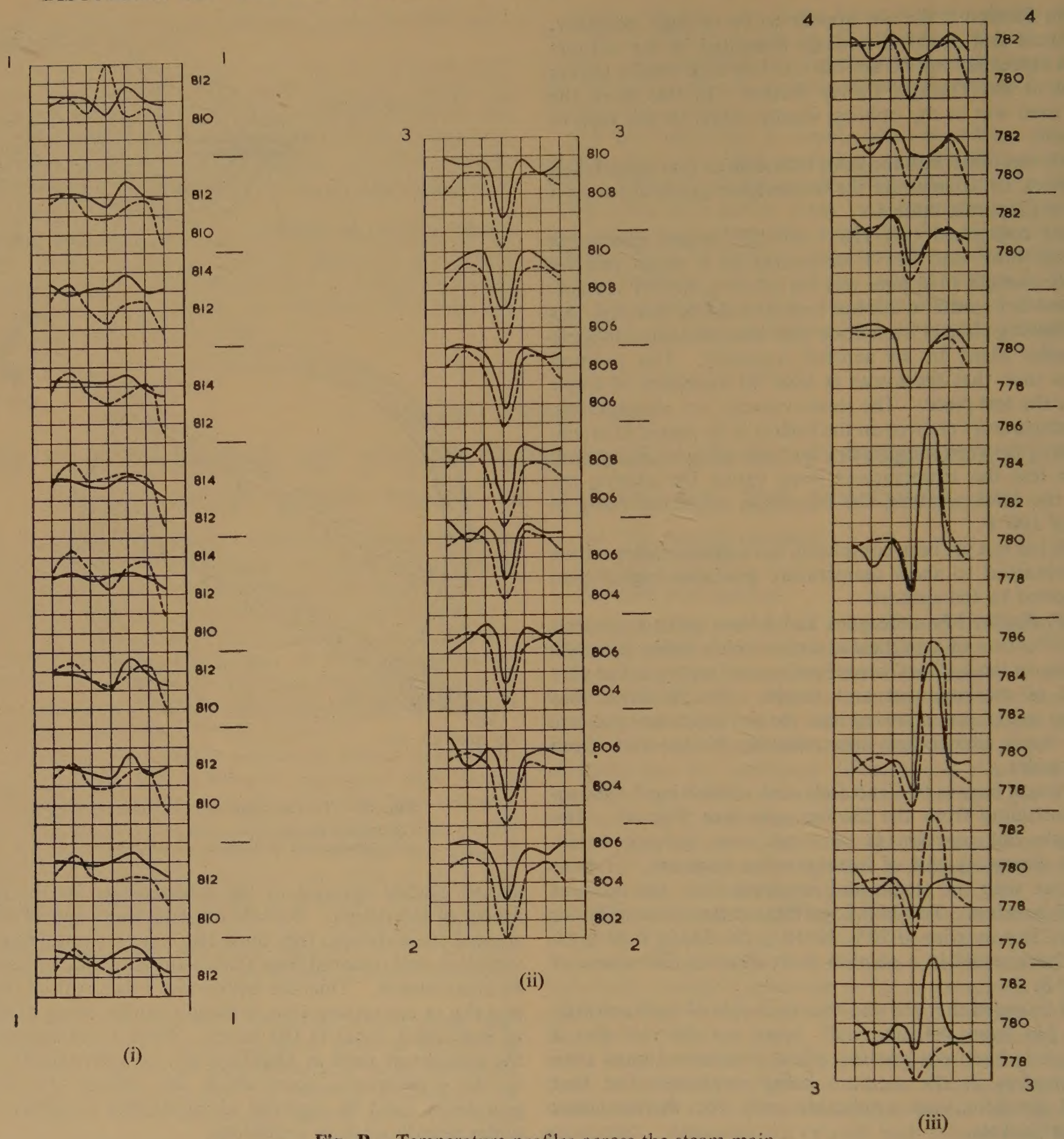

Fig. B.—Temperature profiles across the steam main.

(i) Boilers steaming at equal temperatures and flows.
(ii) Boiler 1 16° F higher than boiler 2, indicating a stream 4° F cooler at the middle of the pipe.
(iii) Boiler 1 64° F higher than boiler 2, showing a transient temperature difference of 9 F°.

Mr. H. Cahm: I note that the previous speaker has mentioned the measurement of the temperature of water flowing in pipes. I should also like to refer to the flow not of steam or water but of hot air, and furthermore a mixture of hot air and hot pulverized fuel. Can the authors say whether there is any comparison between the temperature variation of such mixtures flowing in lagged pipes and the behaviour of steam as dealt within the paper?

Messrs. D. H. Lucas and **M. E. Peplow** (*in reply*): We were pleased to hear from Mr. Thomas that one of our recommendations had been put into practice in a power station. In reply to his question, we consider a plug in the neck of the pocket is quite adequate to prevent undue convective cooling of the thermometer. We agree that thermocouples are more likely to be successful in practice than resistance thermometers.

We were extremely interested in the practical work described by Mr. Whitfield and Mr. Smith. The variations in temperature they measured appear to be random in nature and not correlated to any cause such as the temperature difference between the two steam supplies. In spite of this evidence of appreciable temperature variation we still consider that the mixing which occurs in a steam pipe is so effective that temperature variations across the pipe are very small. We are glad to hear the work is still proceeding and we shall be interested in the outcome.

We agree with Mr. Kirby; we are at present working on the design of a pocket and thermocouple combination which will have mechanical reliability, a high speed of response and also high accuracy and stability.

In reply to Mr. Cahm, the results given for steam will apply approximately in the case of air, provided that the Reynolds number is the same in the two cases.

PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, JUNE 1957

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